THE UNIVERSITY OF ALBERTA

EVALUATION OF ASPHALT CONCRETE MIXES WITH RESPECT TO THERMAL CRACKING

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled

EVALUATION OF ASPHALT CONCRETE MIXES

WITH RESPECT TO THERMAL CRACKING

submitted by Walter Peter Hahn

in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

This investigation considered the effect of various asphalt cement supplies and aggregate sources on the tensile properties of asphalt concrete mixes at low temperatures. Specimens having the recommended Marshall mix design properties of thirteen 1966 highway projects were reproduced and tested using the tensile splitting test at $0^{o}F$.

From signals generated by a load cell and two linear variable differential transformers, the load/strain curve for each test was plotted on an X-Y recorder. Tensile failure strain was found to be a significant indicator of differences between test series made with various asphalt cement supplies. Mix design did not appreciably affect the failure strains of the asphalt cement supply series which exhibited the lowest average failure strains. Desirable Marshall Stability Test properties do not preclude low strain capability in the tensile splitting test.

Both tensile failure strain and asphalt cement supply were found to be related to previous cracking performance. A practical test method was developed for predicting thermal cracking performance at the design stage. Limiting strain values for design purposes have not yet been established. The computer data storage and analysis framework for a continuing study of the cracking of these and other pavement sections, has been outlined.

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CHAPTER I

INTRODUCTION

In areas of the world which have a significant amount of sub-freezing weather, thermal cracking of asphalt pavements is a serious problem. This type of cracking is thought to be caused by thermally induced stresses in the pavement and/or the subgrade. The cracking is not in itself detrimental. It is the loss in serviceability that is associated with cracking that is of concern.

An unserviceable condition due to cracking often precedes the geometric or structural obsolescence of a highway. Thus there is a definite need for research in the field of pavement cracking. Most of the research conducted to date has been directed towards the examination of constructed pavements. It has been found that some pavements crack profusely, while others hardly crack at all. Consequently, a method of predicting performance with respect to cracking, at the design stage, is urgently required.

State of Investigations

Within the framework of the Alberta Cooperative Highway Research Program, investigation of pavement cracking has been conducted since 1963. Attention has been focused on highway sections having a

granular base course. The investigation has included a fairly comprehensive program of both field and laboratory studies. Other investigators in Canada, the United States and Europe have studied the low temperature behavior of asphalt concrete.

It has been observed that asphalt concrete surfaces made with some asphalt cement supplies exhibit a greater amount of cracking. This implies that the capability of an asphalt concrete to comply with tensile stresses and/or strains is a significant property, which is dependent primarily on the asphalt cement supply. The secondary factors of mix design, within supplier variability, construction methods, foundation and environmental conditions must also be considered as causes for cracking frequency differences.

One aspect of the research has been the development of a laboratory test, to be used at the mix design stage, for predicting the cracking behavior of a given asphalt concrete. Gillespie (1966) and Christison (1966) tested a limited number of mix designs, using the tensile splitting test. The results were found to correlate with cracking frequency. More data to substantiate the aforementioned correlation is needed. A further study of the effect of mix design upon the tensile properties of asphalt concrete is also required.

Purpose of the Thesis

On the basis of the severity of the cracking problem in this

region, further investigation is warranted. Specifically, the purposes of this investigation are:

1. To develop an efficient method of conducting a routine tensile splitting test on asphalt concrete.
2. To develop an efficient method of data collection and analysis for a continuing study of the cracking problem.
3. To further substantiate previous conclusions regarding the effect of asphalt cement supply on the tensile properties of a given mix and the occurrence of cracking.
4. To study the effect of various mix designs which utilize the same asphalt supply on the asphalt concrete tensile properties. The objective is to recommend practical modifications in mix design to reduce cracking.
5. To evaluate the practicality of, and the justification for, the tensile splitting test as a routine test for asphalt concrete used in colder climates.

Limitations of the Thesis

Some of the more significant limitations of this thesis are:

1. Insufficient time for the highway sections studied to develop cracking extensive enough to be sensibly interpreted.

2. The use of only one rate of loading in the testing program. This rate was too fast to simulate conditions operative in the field.

3. The use of only one testing temperature ($0^{o}F$).

In addition there are some limitations to the application of the tensile splitting test to asphalt concrete. The elastic theory of the tensile splitting test is being applied to asphalt concrete, which is at the rate of loading used, a visco-elastic material. The mode of failure of the material was such that it was not possible to determine true failure strain. Also, in the test there is a compressive stress acting perpendicular to the tensile stress, whereas in the field only tensile stresses are involved in crack formation.

Organization of the Thesis

Chapter II is devoted in part, to a review and examination of the work done on the mechanisms of cracking and the tensile behavior of asphalt concrete. It is further devoted to a discussion of the application of the tensile splitting test to the study of cracking. Lastly, a review of the theory of the test is given.

Chapter III embodies an outline of the computer application to the study of cracking, and an explanation of the programs used in this investigation.

Chapter IV contains a brief description of the testing procedure and program.

Chapter V is devoted to a presentation of the test results and the comparisons thereof.

Chapter VI includes a discussion of the test procedure, the computer application and the test results obtained.

Chapter VII contains the conclusions drawn from this investigation, the recommendations presented as a result of this investigation, and the recommendations for further study.

CHAPTER II

CRACKING AND THE TENSILE SPLITTING TEST

Mechanisms of Cracking

Some possible mechanisms of thermally induced transverse pavement cracking have been suggested by Shields (1964). The mechanisms are as follows:

1. Simple thermal contraction of the surface.
    - (a) Tensile strength of the asphalt concrete is exceeded by accumulated base course restraint stresses.
    - (b) Tensile strength of the asphalt concrete is reduced by virtue of a rapid surface warming, and may be exceeded by the base course restraint stresses.
2. Freezing shrinkage of the subgrade.
    - (a) Tensile strength of the asphalt concrete is exceeded by the tensile stress at the compressive stress balance points.
    - (b) Same as in 1 (b).

From a consideration of these mechanisms, it would be implied that under a given set of field conditions, resistance to cracking is a function of

asphalt concrete tensile strength. However, Shields (1964) also mentioned that rupture may be dependent on the amount of induced strain. The plausibility of both of these concepts will be subsequently discussed.

Some background data pertinent to this discussion is in order. It is known that sections of asphalt concrete built using certain asphalt cement supplies exhibit markedly more cracking than those built using other asphalt cement supplies. Christison (1966) found that test failure strength did not vary significantly when different asphalt cements were used with the same aggregate. The aggregate effect should be viewed with caution, as Shields (1966) stated that there was only about two to three percent aggregate fracture in field crack cores. Laboratory tests have a considerably higher percentage aggregate fracture. However, even if the aggregate is only a minor factor contributing to strength under field conditions, Sharan (1965) showed that a higher strength asphalt cement was associated with poorer cracking performance.

A possible explanation for the difference in cracking performance between pavements made with various asphalt cements, based on the concept of strength, follows. It is developed by an extension of the work of Hills and Brien (1966). FIGURE 1 shows hypothetical tensile strength curves for asphalt concretes which utilized asphalt cement supplies denoted by A and B. Strength curves similar to those

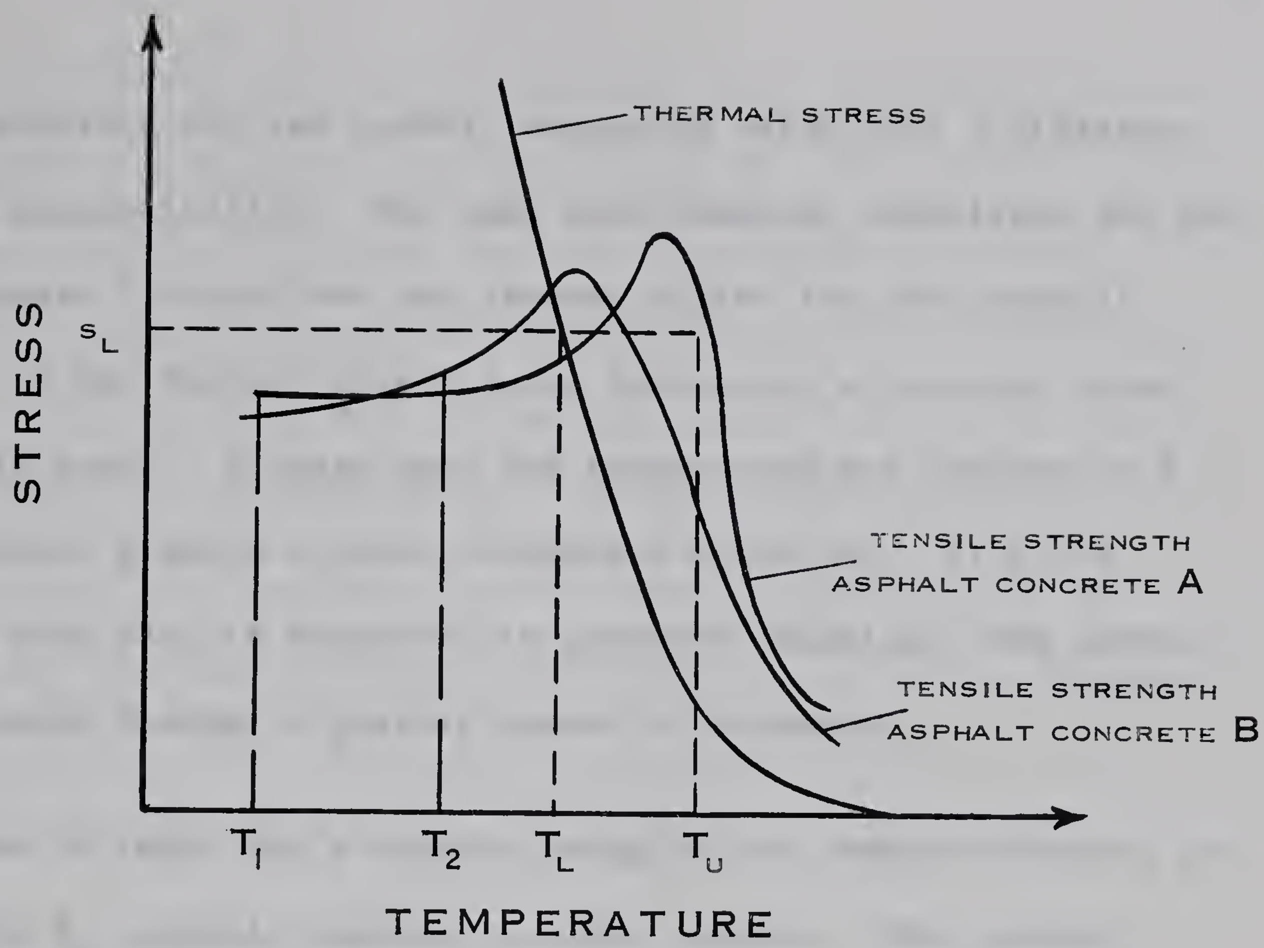


FIG. 1: HYPOTHETICAL STRESS - TEMPERATURE RELATIONSHIP

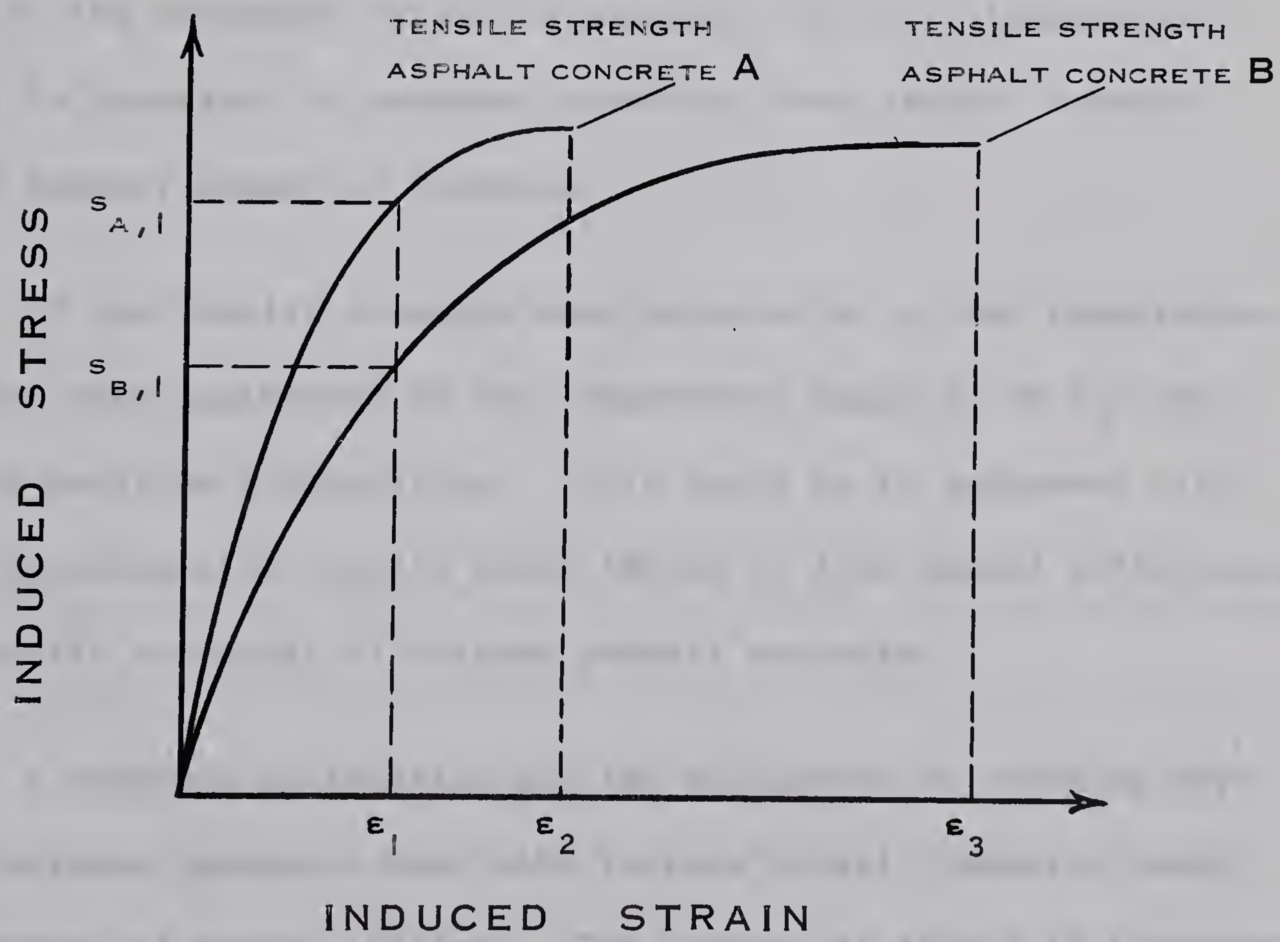


FIG. 2: HYPOTHETICAL STRESS - STRAIN RELATIONSHIP

shown are plausible for two asphalt concretes which have a different temperature susceptibility. The same environmental conditions and the same temperature fluctuations are assumed active for both asphalt concretes. If the thermal stress curve intersects a strength curve, rupture would occur. Suppose that the temperature was lowered to T_L. Asphalt concrete A would rupture, whereas B would not. If it is temperature drop that is important in pavement cracking, then asphalt concrete A would display a greater amount of cracking.

Now if there was a rapid warming of the asphalt concrete to a temperature T_u, asphalt concrete B would rupture. The tensile stress S_L is assumed to remain essentially unchanged. For rupture to occur it is also necessary to assume that plastic flow will be insufficient for the necessary stress relaxation. If it is temperature rise that is important in pavement cracking, then asphalt B would display a greater amount of cracking.

If the tensile strength were measured at a test temperature and loading rate equivalent to the temperature range T_1 to T_2, the difference would be insignificant. This would be in agreement with previous investigation results which failed to find marked differences in the tensile strengths of various asphalt concretes.

A possible explanation for the difference in cracking performance between pavements made with various asphalt cements, based on the concept of strain, follows. The concept of strain is introduced

because it is felt that under field conditions a consideration of strength is not as realistic. Suppose as before, that we have a given tensile stress due to thermal contraction or subgrade shrinkage. It is known that if asphalt concretes, say A and B, display marked field cracking differences, then their respective test failure strains will be significantly different (Gillespie (1966), Christison (1966)). The failure strain for the more cracked asphalt concrete will be smaller. Under the same environmental conditions, assuming similar thermal coefficients for A and B and/or subgrade shrinkage, a given stress with associated different strains does not seem possible.

What is more likely, is that due to the temperature drop and/or freezing shrinkage, there is a tendency for the asphalt concrete to shrink. Since the surface is restrained and virtually no deformation is possible, strain is induced in the surface. For a given value of strain, say ε_1 in FIGURE 2, the associated values of stress are $s_{A,1}$ and $s_{B,1}$. In summary, it appears that a given set of conditions will induce a given strain which is then associated with different stresses, which depend on the stress/strain characteristics of the asphalt concrete.

Referring to FIGURE 2, an induced strain anywhere within the range of ε_2 to ε_3 would be sufficient to cause rupture of A, but not of B. If the imaginary relative magnitudes of failure strains shown in FIGURE 2 are consistently obtainable in practice, then the reason

for marked differences in cracking frequency between supplies is evident. Asphalt concretes similar to B exhibit a greater degree of viscous flow at low temperatures than those similar to A. What intrinsic properties of the asphalt cement that cause these marked differences is not known.

If the above postulation is correct, it does appear that there would be an approximate limiting strain under any set of test conditions, which would preclude unsatisfactory cracking performance. Shields (1964) has mentioned the possibility of there being some limiting strain for a tensile failure.

Determination of such a limiting strain for asphalt concrete from theoretical considerations would be a complex problem. Monismith et al. (1965) have presented a method of calculating the thermal stress in an asphalt concrete for any set of conditions. Possibly a somewhat similar approach could be used to arrive at values for temperature induced strain. Then the strain for the worst probable realistic set of conditions (highest rate of temperature drop) could be determined and used as the limiting strain value for design purposes. Such a theoretical calculation for estimating the magnitude of strain induced by freezing shrinkage would probably not be practical. Some subgrade cracks are so wide that no manipulation of the asphalt concrete properties would help. However, keeping the strain capability high would certainly minimize reflection of the smaller subgrade cracks. The alternative method of

establishing an approximate limiting strain value for laboratory tests, is to correlate the test failure strains with field cracking frequency.

The concept of a limiting strain is somewhat difficult to apply in connection with mechanisms 1(b) and 2(b), suggested at the beginning of this chapter. Shields (1964) recognized this difficulty. It would seem that if the same amount of induced strain was operative after a rapid warming, the compliance of the asphalt concrete to such a strain would be greater. However, there is the possibility that the increase in compliance would be insufficient to offset a rapid drop in the strength of the material. Before any firm postulations are made, it will be necessary to know under precisely what thermal conditions failure does occur. At present this is not known.

Tensile Behavior of Asphalt Concrete

Having examined the mechanisms of cracking, it is now pertinent to briefly review and comment on some of the more recent investigations concerned with cracking.

Culley (1966) reported on a field investigation of pavement cracking in Saskatchewan. Both asphalt source and grade were found to be significant with respect to cracking. Transverse cracking became evident after prolonged cold temperatures followed by a sudden rise in temperature. This observation does not support the limiting strain postulation. However, during periods of warmer weather the rate of

temperature drop of the surface asphalt concrete during the cooling hours may be greater than during cold weather. It is the rate of inducement of strain that is important, as well as the ambient temperature. If the rate is too fast for viscoelastic compliance, rupture would occur. Gillespie's (1966) plots show that the failure strains of asphalt concretes at lower temperatures tend to approach a limiting value, i.e., below about $0^{o}F$ there is almost no change in failure strain for a given asphalt concrete. Also the induced strains due to thermal contraction of the surface would be less for a given temperature drop below the glass transition temperature. So since the two above mentioned factors become less important at lower temperatures, it may be possible that a higher rate of temperature drop at warmer temperatures is critical.

The observation of Foster (1965) is of interest in this connection. It was observed, under test traffic conditions, that cracking took place on a warm day following a thunderstorm. The asphalt concrete had been rapidly cooled and the strains induced by the loads were too great to be counteracted by viscoelastic compliance. Although in this example the cracking is load associated, it does emphasize the detrimental nature of rapid drops in pavement surface temperature.

Both Gillespie (1966) and Christison (1966) have presented extensive reviews of work done on the tensile behavior of asphalt cement and asphalt concrete. Only some of the recent investigations not reported will now be discussed.

At the 1966 meeting of the Association of Asphalt Paving Technologists a symposium on "Non-Traffic Load Associated Cracking of Asphalt Pavements" was held. In the introductory statement Marker (1966) stressed the point that several interrelated factors are probably at work at the same time where cracking is occurring. In the previous discussion of the mechanisms of cracking it was not intended to imply that the mechanisms cited were independent, nor that they were the only contributing factors.

Anderson et al. (1966) have outlined work done on thermal cracking within the framework of the Alberta Cooperative Highway Research Program since 1963. They emphasized that the drastic loss of serviceability due to transverse cracking is a serious problem. The exact mechanism promoting cracking was not yet clear. More cracking appeared to be associated with certain asphalt cement supplies, but present conventional laboratory data does not explain the differences in performance.

Schmidt[1] (1966) also pointed out that there seems to be a difference in the ability of various asphalt concretes to adjust to slow tensile strains without cracking. In this connection it was concluded that as asphalt cement content increased, so did cracking resistance. Also, the glass transition temperature of the asphalt cement appears to correlate better with fatigue resistance at low temperatures than the viscosity. The flexural fatigue tests cited

by Schmidt were carried out at a constant strain amplitude. This would appear to be much more representative of field conditions than to use a constant stress.

Studies dealing with cracking due to absorptive aggregates and due to volume changes in the underlying materials respectively, were reported. These mechanisms would contribute primarily to cracking not of a thermal nature.

In the symposium discussion Fromm (1966) stated, that based on some studies in Ontario, asphalt cement supply and properties of the granular base course were significant with respect to cracking frequency. Both Serafin (1966) and Hindermann (1966) have mentioned the occurrence of winter subgrade cracking in sandy areas. This indicates that the subgrade need not necessarily be plastic to exhibit freezing shrinkage.

Puzinauskas (1966) made the observation that a higher rate of loading and/or lower temperature in a flexural test on asphalt concrete produces more aggregate fracture. Also the portion of the fracture surface not passing through the aggregate appears to be the result of an asphalt adhesion failure. Schmidt[2] (1966) stated in reply, that the asphalt cement failure was actually cohesive in nature as the unbroken aggregate particles were still coated. This apparently was also true of field crack cores Schmidt examined. Shields (1966) expressed the opinion that both cohesion and adhesion failures were

present in the asphalt cement phase of field crack cores.

Application of the Tensile Splitting Test

Although the mechanisms of pavement cracking and the tensile behavior of asphalt concrete was not fully understood, it was necessary due to the severity of the problem in this region, to devise a laboratory test which could be used to predict field performance. Since it appeared that cracking frequency differences were associated with asphalt cement supply, different asphalt cements were first tested. Sharan (1965) tested two asphalt cements, one from a badly cracked and another from an uncracked section of pavement. The testing consisted of applying varying rates of tensile deformation to variable film thicknesses at various temperatures. For any given set of conditions, asphalt cement from the badly cracked section exhibited a higher strength and a lower strain to failure.

Since under field conditions it is the fracture of the asphalt concrete that is of concern, Gillespie (1966) contrived a test method for asphalt concrete, utilizing the tensile splitting test on Marshall mix design specimens. The variables were two supplies of asphalt cement (from high and low cracking frequency sections), three different asphalt contents, and four different test temperatures. Results were analogous to Sharan's (1965). Also, no relationship could be established between any data derived from the Marshall mix

design method, and the cracking frequency. Thus the need for a tension test for asphalt concrete was confirmed. The tensile splitting test was found to be practical because it utilized the same specimens as the present mix design method, and it was simple to conduct.

Christison (1966) tested field cores and Marshall specimens using the same test method at only $0^{o}F$. The results again showed that the occurrence of transverse cracking increased with a decrease in failure strain. Failure strain appeared to be a function of the asphalt cement supply. He further concluded that the tensile splitting test was a practical test method for the determination of the low temperature properties of asphalt concrete.

Breen and Stephens (1966) used the tensile splitting test to test asphalt concrete at temperatures of from $40^{o}F$ to $0^{o}F$. They used the work to fracture (product of the load and the loading movement) as an indication of the low temperature cracking resistance. No correlations to field performance were mentioned.

Theory of the Tensile Splitting Test

The testing method consists simply of loading a cylinder via loading strips, across a diameter in a compression testing machine. The test was developed independently, and introduced almost simultaneously by F. Carniero of Brazil and M. Akazawa of Japan. Although the test was originally intended for cement concrete, it could conceivably be used

for any material which satisfied the theoretical considerations.

The theory of the tensile splitting test applies to materials that:

1. are elastic, and
2. have a compressive strength at least three times the tensile strength.

Asphalt concrete does not satisfy condition 1 even at low temperatures. The effect of the departure from elasticity would seem to be to relieve stress concentrations, and thus cause a more uniform stress distribution within any portion of a specimen (Wright (1955), Peltier (1954), Mitchell (1961)).

Frocht (1948) has developed equations describing the stress conditions produced by a concentrated load acting on the edge of a semi-infinite plate. The external concentrated load is assumed to act only as a stress on a semicircular groove. The stress components are then determined by choosing a function that satisfies the compatibility equation.

A circular area is then removed from the plate and a stress is applied to the circumference, which will maintain an unchanged stress condition. The general expression for the state of stress at any point within the disc is then derived. Therefrom the theoretical stress distribution on the vertical diameter can be deduced. There is a uniform

horizontal tensile stress and a variable vertical compressive stress. The magnitude of the compressive stress directly underneath the point load is infinite. Consequently, in this theoretical case, failure by local compression is imminent. However, in practice the load is distributed by means of loading strips.

Wright (1955) has modified the theory to account for the distribution of the applied load. The approximate equations for the stress on the vertical diameter when the widths of the loading strips are less than d/10 are:

$$\text{Vertical stress} = -\frac{2P}{\pi td}\left[\frac{d}{2a}(\alpha + \sin\alpha) + \frac{d}{d-r} - 1\right]$$

$$\text{Horizontal stress} = \frac{2P}{\pi td}\left[1 - \frac{d}{2a}(\alpha - \sin\alpha)\right]$$

where P = applied load

t = thickness of the specimen

d = diameter of the specimen

a = width of the loaded area

α = angle subtended by the loaded area at the point considered

r = distance from the loaded area to the point considered

Over the central three-fourths of a specimen, where α is very small, the horizontal stress is essentially a uniform tensile stress of magnitude $\frac{2P}{\pi td}$.

Even with this distributed load the question of a local compression failure directly under the loading strips arises. However, it can be shown by substitution into the equations for vertical and horizontal

stress that the magnitudes of the vertical and horizontal compressive stresses under the loading strips are similar. This is somewhat analogous to the conditions in a triaxial test. Consequently the tensile failure which does occur in practice is not in conflict with the theory.

Both Gillespie (1966) and Christison (1966) have given an extensive coverage of the theory connected with the tensile splitting test. Diagrams of stress distributions, which may be helpful in acquiring an understanding of the theory, are contained therein.

CHAPTER III

COMPUTER APPLICATIONS

General

In pavement evaluation programs, several agencies have found it advantageous to use computer data storage and analysis. The Canadian Good Roads Association (1959) conducted a nationwide pavement study with the aid of electronic computer equipment. During the course of the AASHO Road Test investigations, a large volume of data was processed and analyzed by computer methods.

Computer application to the study of thermal cracking is beneficial because,

1. it provides an effective means of data storage, and
2. it provides an efficient method of data analysis.

When considering a highway system cracking study, the amount of necessary background data is voluminous. The consistency and efficiency of manual data storage is dependent upon the consistency and efficiency of the employees. A computer storage system has the advantage that it can be made invariable by placing a screening program between the input and the storage.

When a cracking analysis of several highway sections is

initiated, data describing the complete history of those sections is required. Inconsistency in the data between sections precludes economical computer application. However, if the data storage is invariable, the same method of analysis (same computer program) can be imposed on the whole highway system, with a considerable saving in time and expense.

FIGURE 3 shows a flow diagram for a proposed data collection scheme suited to the study of pavement cracking. This flow diagram will be discussed subsequently. It should be noted that the flow diagram presented is not intended to be a rigid format for the investigation of thermal cracking. It is intended to be a conceptual guide. Only two of the six "blocks" shown have been completed, so the remaining four have received only a rather limited treatment.

Inventory Program

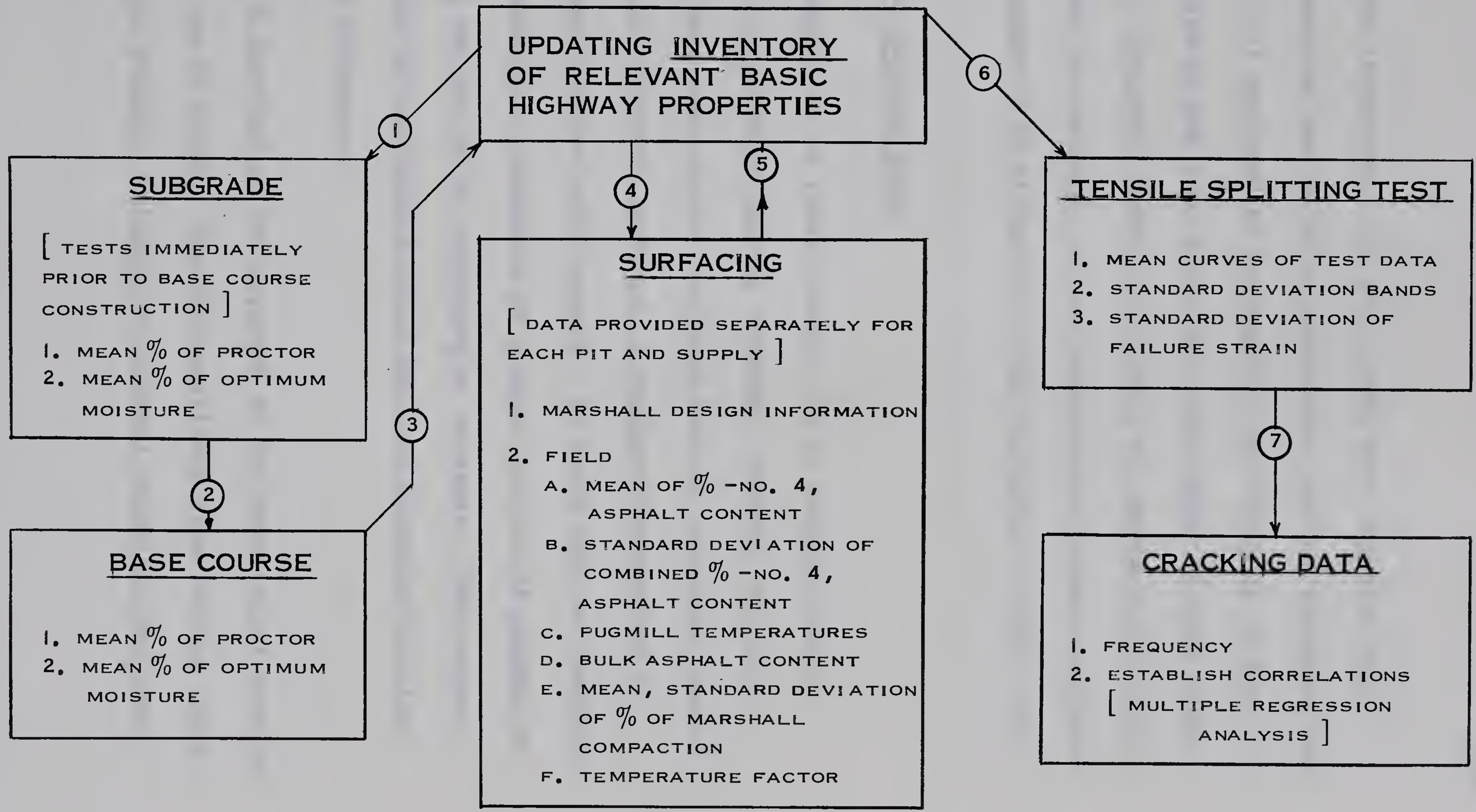
The purpose of the inventory program is to provide an updating inventory of basic highway properties. Each inventory section at any stage, is unique with respect to the input variables. The inventory sections form the basic storage units for future data. It is suggested that a minimum length of inventory section be adopted. This was not done in this investigation. The inventory program, a detailed explanation of the program and the output is contained in Appendix D.

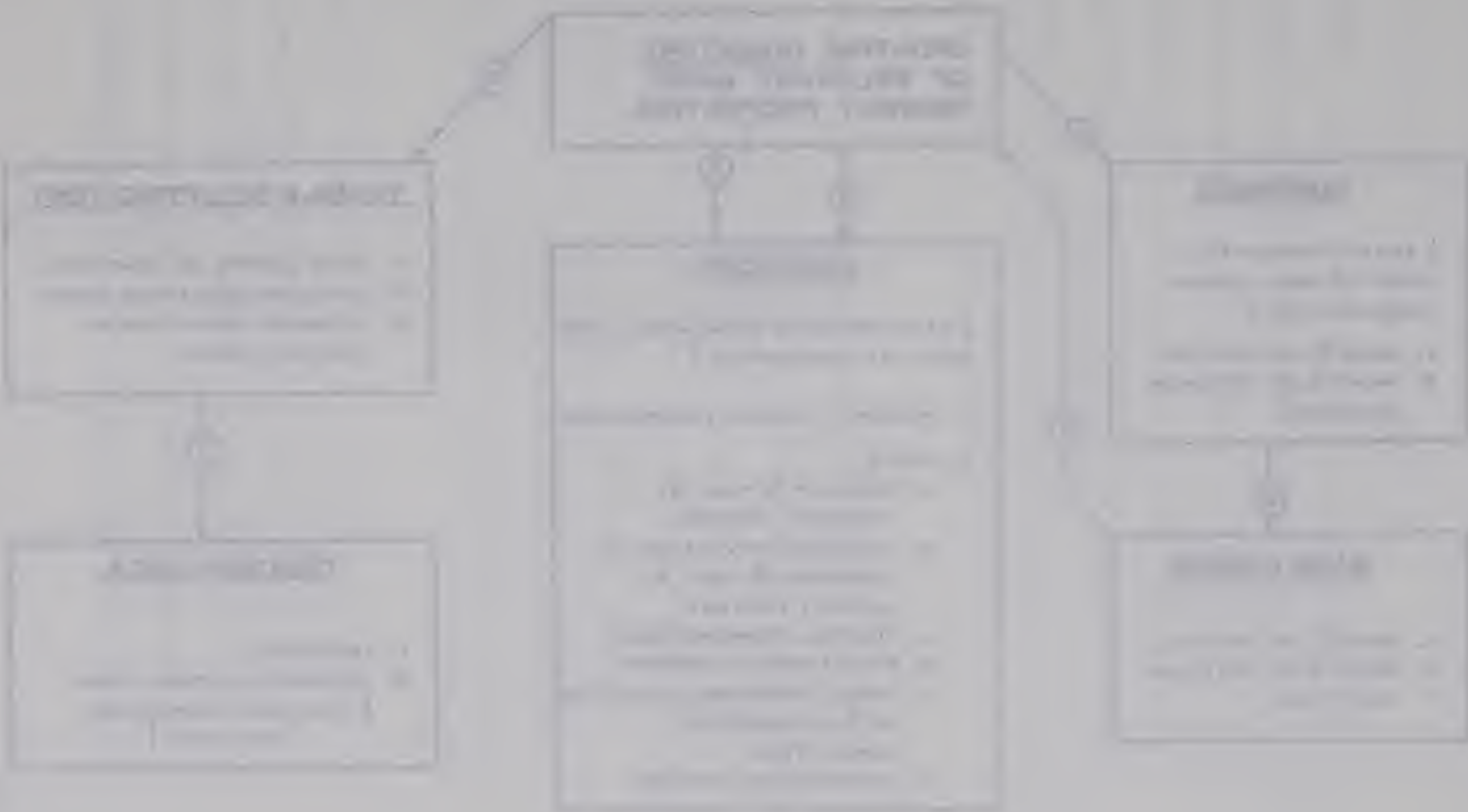
Only the highway sections of which the mix designs were tested,

FIG. 3: FLOW DIAGRAM FOR COMPUTER ANALYSIS OF THERMAL CRACKING

[USING ROUTINE TEST DATA]

NOTE- ALL DATA IS SORTED INTO INVENTORY SECTIONS





were included in the inventory. All data cards were supplied simultaneously to the program, and only the completely updated inventory was produced. However, if desired, it is possible to obtain up to date inventory information at any time after the first stage of data cards has been provided. Inventory information could be combined with other information relevant to cracking, as such information became available. The next few paragraphs will elaborate on the inclusion of other data.

Analysis Method for Routine Tests

The inventory is in itself useful, as it supplies basic information about a particular highway section. However, if this basic information were coupled with analyzed routine test data, sorted into the appropriate inventory sections, a complete description of each distinct highway section would result. It would then be possible to determine all available properties of a given portion of highway by simply designating the end point chainages or mileages. The output could be in the form of two printed lines for each inventory section within the portion designated.

A brief discussion of the approach to the handling of routine test results will now be given. Any data available from routine tests which was considered possibly relevant to thermal cracking, has been included.

A. Subgrade

The quality of the compaction and the degree of saturation appears to be significant. Soil type is also important, but has already been included in the inventory. It would be reasonable to use the subgrade density results, taken prior to the base course application. It is suggested that the mean percent of Proctor density be used as a measure of the relative compaction. The field moisture content expressed as the mean percent of optimum would give an indication of the degree of saturation of the soil.

B. Base Course

The same data extracted from the field density test as was used for the subgrade is considered significant. Consequently the same computer program could be used for manipulation of the input data. No statistical analysis has been suggested for the subgrade or the base course data because often the number of tests within an inventory section will be few. The number of density tests used to find the means for each inventory section should be placed into storage.

C. Surfacing

Field data would have to be supplied separately for each aggregate pit and asphalt supply. Similarly the Marshall design information would be given by pit and supply, and could be stored into all the appropriate inventory sections.

As an indication of paving plant control, it is suggested that

the routine extraction test could be used. These tests are reported by highway location, so they could readily be sorted into inventory sections, and the necessary calculations could be performed on the results. The percent passing the number four sieve and the percent asphalt content should be combined in a manner similar to that recommended by Huculak (1964). The standard deviation of the asphalt content from the optimum mix design line, with penalty factors applied to points outside the allowable gradation band, would give an indication of plant control. The mean values of gradation and asphalt content would show the degree of conformity of the field construction to the design. Again, the number of tests in each inventory section should be included. If the number of tests is less than the minimum recommended by the American Society for Testing and Materials (1966), Designation E122-58, the standard deviation should not be computed. Twelve tests should probably be considered an absolute minimum.

It would be desirable to include plant pugmill temperatures expressed as an average deviation from the optimum mixing temperature. This would reflect any improper mixing or abuse of the asphalt cement. The overall bulk asphalt content for each aggregate pit and supply should be included and compared with the average extracted value.

The field compaction expressed as a percent of Marshall density could be used to calculate the mean degree of compaction, and the variability of such compaction, for each inventory section. Air,

pavement and rolling temperatures would be useful. However, it is difficult to present such data, which may have been collected over a long period (especially for larger inventory sections), in a concise, yet meaningful form. Perhaps it would be expedient to use the average of each air and pavement temperature as input. The cumulative degrees below, say 45°F, divided by the number of readings below 45°F, could be expressed as a factor for each inventory section.

Reliable test data on asphalt cement properties would constitute beneficial input. This would be particularly so if approximate field locations, which the asphalt cement samples represented, were known. Each inventory section could then be assigned the appropriate asphalt cement test properties.

Tensile Splitting Test Analysis

The tensile splitting test "block" follows the surfacing "block," since to date this has been the order. However, if this test were to become part of the routine asphalt concrete design procedure, then this data would be inserted with the Marshall design information.

The program for the analysis of the tensile splitting test performed some laborious, repetitive calculations. For each test, the data punched onto a computer data card included,

1. the load at each 0.0001 inch deformation increment (which was equal to strain since a 1 inch gauge length was used), taken directly from the test curve,

2. the specimen number,
3. the specimen diameter and thickness,
4. the aggregate pit,
5. the asphalt penetration, and
6. the asphalt supply.

The calculations performed by the program, for each test series, were

1. a conversion of applied load to tensile stress,
2. a computation of the coordinates of the average stress/strain curve,
3. a computation of the upper and lower two standard deviation bands for the stress, and
4. a computation of the two standard deviation bands of the failure strain.

The deviation bands for the stress were determined only to show the magnitude of dispersion inherent in the tests performed. Deviations of failure strain will be used later to determine confidence limits for the average failure strain. The computer program and the output for one test series is given in Appendix D.

Cracking Data and Analysis

As cracking data is obtained, it could be sorted into inventory sections and the average number of cracks per mile could be computed. When a substantial number of inventory sections had been completed, analysis could be performed. Ideally all the granular base course highway

sections in the system would be included. With all the supposedly significant variables which affect cracking in storage in unique inventory sections, a multiple regression analysis could be performed. The relative importance of the input variables would thus be evaluated.

It is very important that the results obtained from such a regression analysis be studied carefully, and that the reasons for correlation be understood before instituting any radical revisions. As a significant amount of new data became available, the analysis should be re-run. The larger the sample became, the more confidence could be placed in the results. The effect of changes made would be readily observable. Periodic revisions would be necessary in the data accumulation system and in the analysis method as new techniques and ideas became available. Broadening of the system to encompass materials problems other than cracking is envisioned.

CHAPTER IV

TESTING PROCEDURE AND PROGRAM

Apparatus

FIGURE 4 shows a block diagram of the complete testing apparatus. Testing was done in the frost room at $0^{o}F$. Asphalt concrete Marshall specimens were tested using the tensile splitting test. These specimens are approximately four inches in diameter and two and one-half inches in thickness, and were prepared according to ASTM Designation: D1559-65. The electrically activated recording equipment was placed in an adjoining room. Specimen temperature was monitored by means of a Thermo Electric pyrometer indicator whose sensor was embedded in a Marshall specimen. Two thermometers within the frost room were periodically read to check the pyrometer readings.

A Wykeham Farrance compression tester was used to load the test specimens. The applied load was measured by a Kwoya Musen load cell which was placed upon the lower platen of the compression tester. Two Sanborn linear variable differential transformers connected in series, and attached to opposite ends of the specimen, measured the deformation over a one inch gauge length centered on the horizontal diameter. The sum of the deformations was considered to be twice the average strain. FIGURE 5 shows the compression tester and a specimen

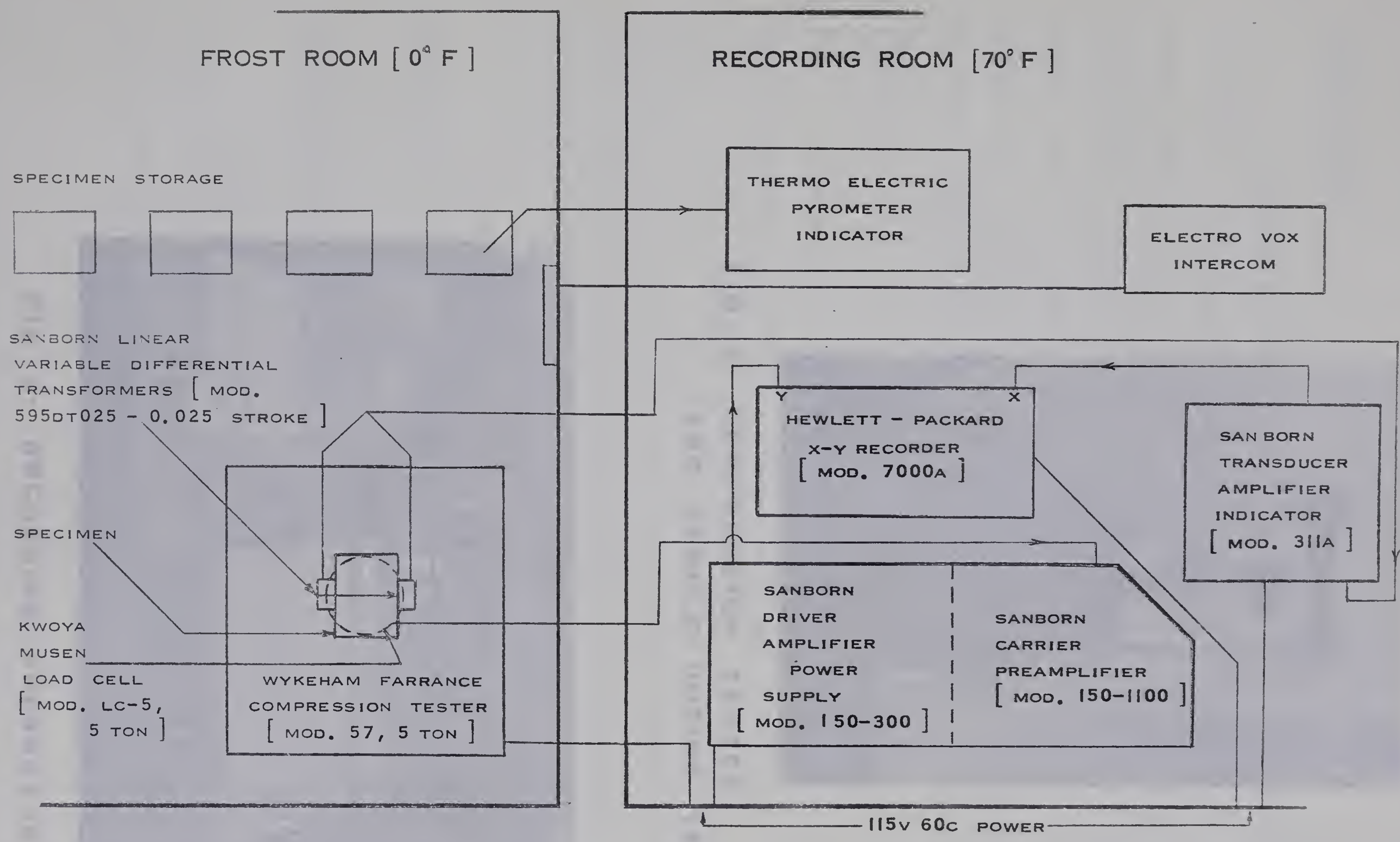


FIG. 4: BLOCK DIAGRAM OF TESTING APPARATUS

FIG. 5: COMPRESSION TESTER AND SAMPLE DURING TEST

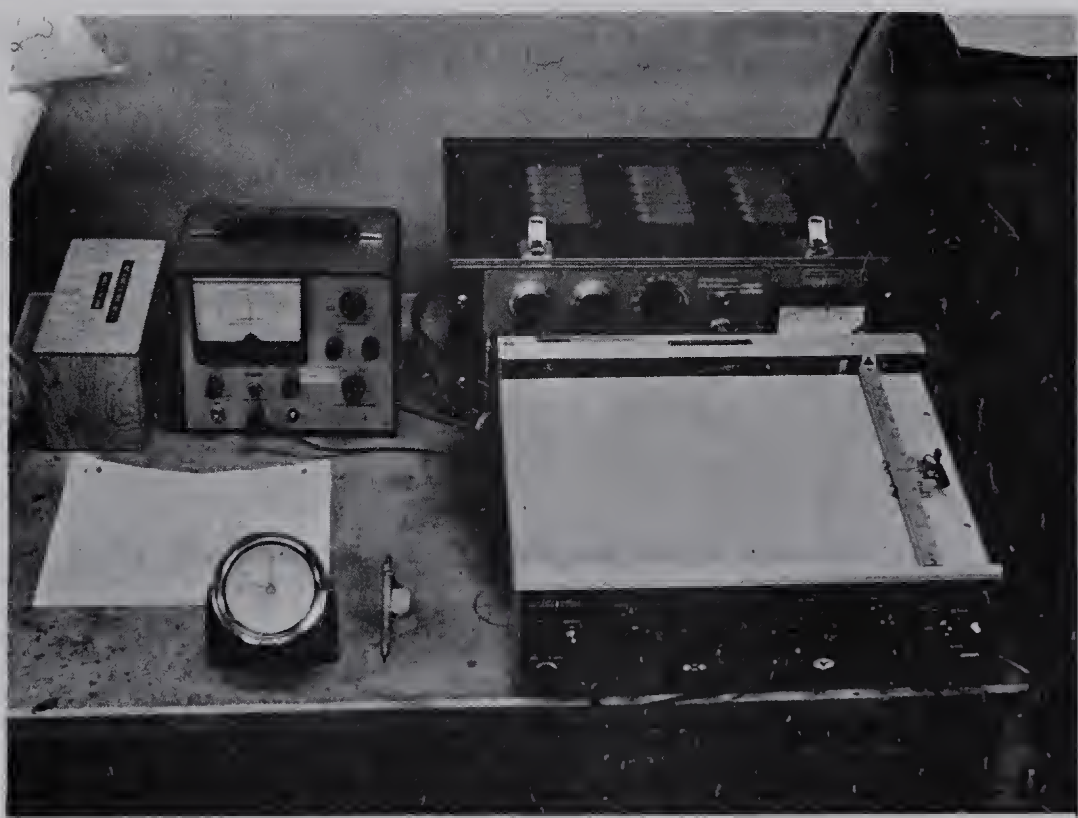


FIG. 6: RECORDING APPARATUS

during a test.

Both the load cell and the strain gauges were electrically activated by their respective amplifiers. The load cell was connected to the combined Sanborn driver amplifier and power supply, and carrier preamplifier. Applied load measurement was in the form of a proportional output electrical signal to the aforementioned unit. The strain gauges were connected to a Sanborn transducer amplifier, which received an output signal proportional to the average strain measured by the two gauges.

The output signals were fed through the amplifiers to a Hewlett-Packard X-Y recorder. Load response was transmitted to the Y axis and strain response to the X axis. During the course of a test, both load and strain response were present, which resulted in a load/strain trace on the recorder paper. FIGURE 6 shows the X-Y recorder and the two amplifiers in the recording room during a test.

Appendix A contains a description of all the testing apparatus used in this investigation.

Outline of Calibration Procedures

The load cell and the strain gauges were calibrated to convenient scales on the X-Y recorder, using known increments of load and deformation respectively. Appendix B contains a description of the

calibration procedures as well as pertinent calibration curves. Only a brief outline follows.

For the load cell calibration, load was applied by means of a previously calibrated compression tester. Calibration at room temperature onto the Y axis of the X-Y recorder was satisfactory, since the load cell was a full bridge, temperature compensating device. Accuracy of the calibration was of course limited to the accuracy of the compression tester dial readings. However, in this investigation comparative values between tests were considered of greater importance than absolute values.

For calibration of the strain gauges it was necessary to design and construct a calibration device, which will be subsequently referred to as a "gauge calibration jig." FIGURE 7 shows both strain gauges affixed to the gauge calibration jig and ready for calibration. Steps in the gauge calibration were as follows:

1. Calibration of the dial gauge, which is part of the gauge calibration jig. This was done using commercially produced, highly accurate, machinist's gauge blocks.
2. Preliminary calibration for gauge selection. Three gauges were calibrated separately at room temperature to determine which two were most closely matched.
3. A careful calibration of each of the two chosen gauges at room temperature. One gauge was held at the null position

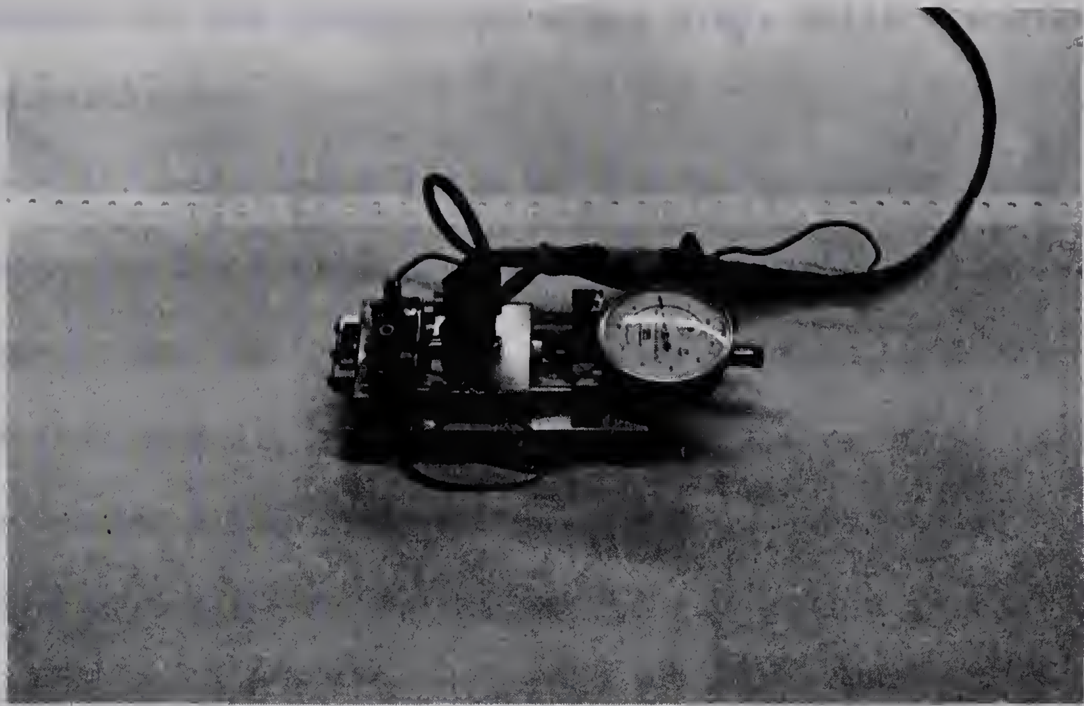


FIG. 7: STRAIN GAUGES POSITIONED FOR CALIBRATION ON GAUGE CALIBRATION JIG

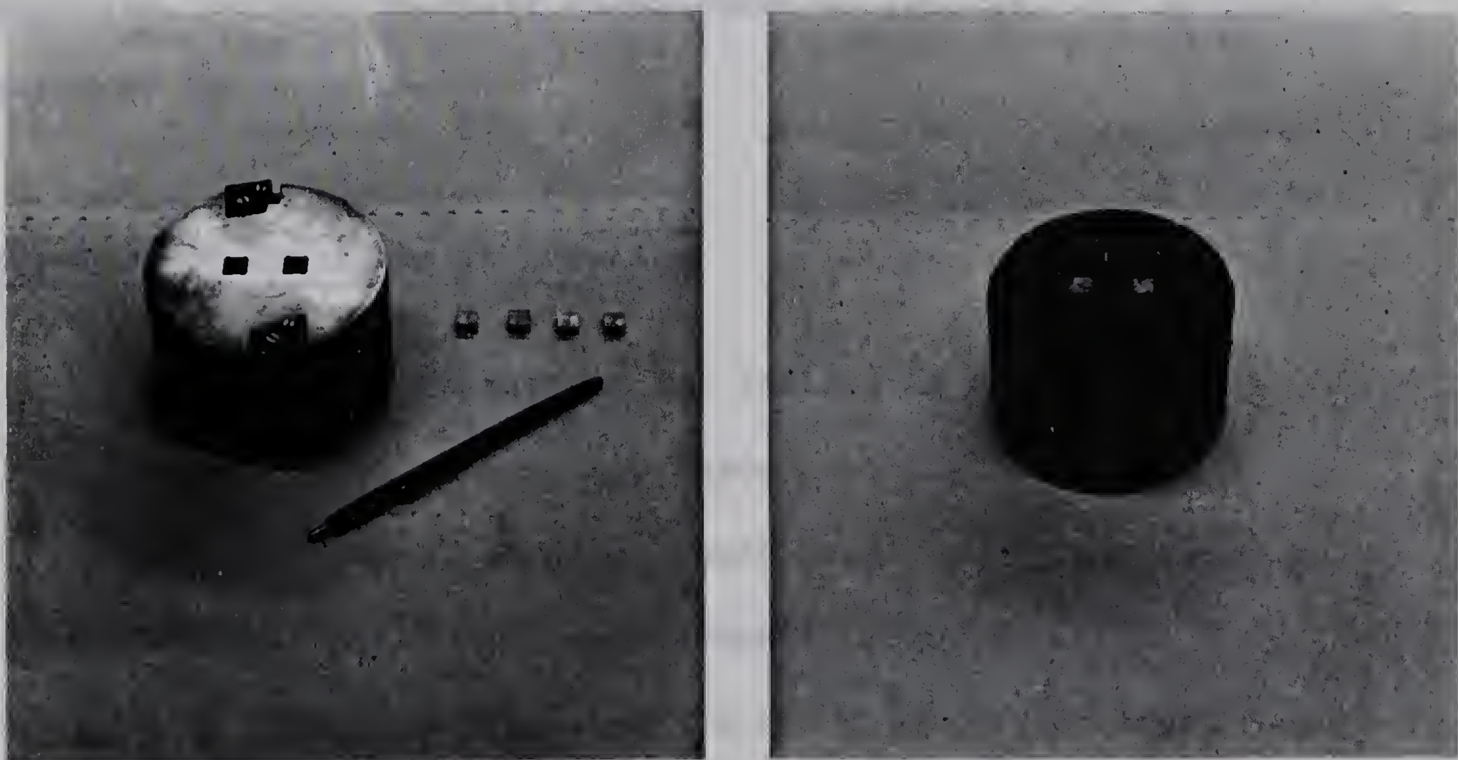


FIG. 8: SPECIMEN BEFORE AND AFTER ATTACHMENT OF GAUGE POINTS

(placed off the gauge calibration jig), while the other was calibrated.

4. A simultaneous calibration of the two gauges at room temperature. This was done to determine the difference between the sum of the two separate signals, and the combined signal. Since the two gauges were wired in series the difference should have been negligible.
5. A simultaneous calibration of the two gauges in the frost room at $0^{o}F$, to establish an accurate scale on the X axis of the X-Y recorder. This was necessary since these gauges were not temperature compensating.

For the sake of convenience only step 5 was performed at the test temperature, as only relative values were of interest in the previous comparative calibrations.

Preparation of Specimens for Testing

Specimens were prepared for testing as follows:

1. The specimen number, aggregate pit, asphalt cement penetration and asphalt cement supply were recorded.
2. The average of four measurements (using a dial caliper) of the diameter and the thickness of each specimen was recorded to the nearest 0.01 inch.
3. Loading points for each specimen were marked with a

crayon through slots in the gauge point jig shown in FIGURE 8. This procedure insured that the loading points were on the same diameter of the cylindrical specimen, and that the gauge points were perpendicular to this diameter.

4. Each gauge point was coated on one side with warm 200/300 penetration asphalt cement and set aside. The gauge points were 3/8 x 3/8 x 3/16 inch brass plates.
5. The gauge point jig was set on one end of a marked specimen and carefully aligned with the crayon marks. Two coated gauge points, which had been allowed to cool, were inserted into the holes in the gauge point jig. They were then firmly pressed onto the specimen.
6. The specimen was inverted and the same procedure was repeated. Gauge points already affixed were not disturbed because the specimen was now elevated about 3/8 inch by props.
7. Each specimen was placed into the frost room or a freezer, depending on whether testing was in progress. The asphalt cement holding the gauge points hardened and firmly affixed gauge points resulted. FIGURE 8 shows a specimen with gauge points attached.

Outline of Test Procedure

Specimens remained in the frost room at $0^{o}F$ a minimum of eight hours prior to testing. The sequence of operations performed during the course of a test were as follows:

Positioning of the Specimen

1. The specimen to be tested was inspected to assure that the gauge points had not slipped from their proper position.
2. A plywood strip 3/16 x 1/4 x 3 inches was attached to the top loading block by means of a rubber band.
3. A similar strip was placed upon the loading platen that fitted onto the load cell. Strips of the dimensions used were found to be the most satisfactory on the basis of preliminary testing.
4. The specimen was placed upon the lower loading strip and held while the loading ram was raised by means of a hand wheel.
5. The crayon marks on the specimen were positioned in a vertical plane and then aligned with the longitudinal axes of the loading strips. Some manipulation of the specimen and of the height of the loading platen was required to obtain the proper positioning. It was also necessary to check the alignment of the load cell with

respect to the specimen.

6. The loading ram was raised just enough to prevent movement of the specimen during the attachment of the strain gauges.

Attachment of the Strain Gauges

1. The rear strain gauge core and coil assembly were simultaneously placed onto the gauge points. They were then secured by tightening the allen screws within the respective assemblies.
2. The same procedure was repeated for the front core and coil assemblies.
3. Both sets of assemblies were checked for tightness. A final check on the alignment of the specimen was made.
4. A C-clamp was attached to the side of the specimen where the core assemblies were attached. The purpose was to obviate damage to the assemblies after failure.

FIGURE 9 shows a specimen ready for load application. It should be noted that the strain gauge cores were attached to the core assemblies by threaded rods. An epoxy resin coating was applied to the exterior of the core-rod interface and the rod-assembly body interface. This was done to prevent loosening due to test shocks. Any movement that did occur was detectable by breaks in the coating.

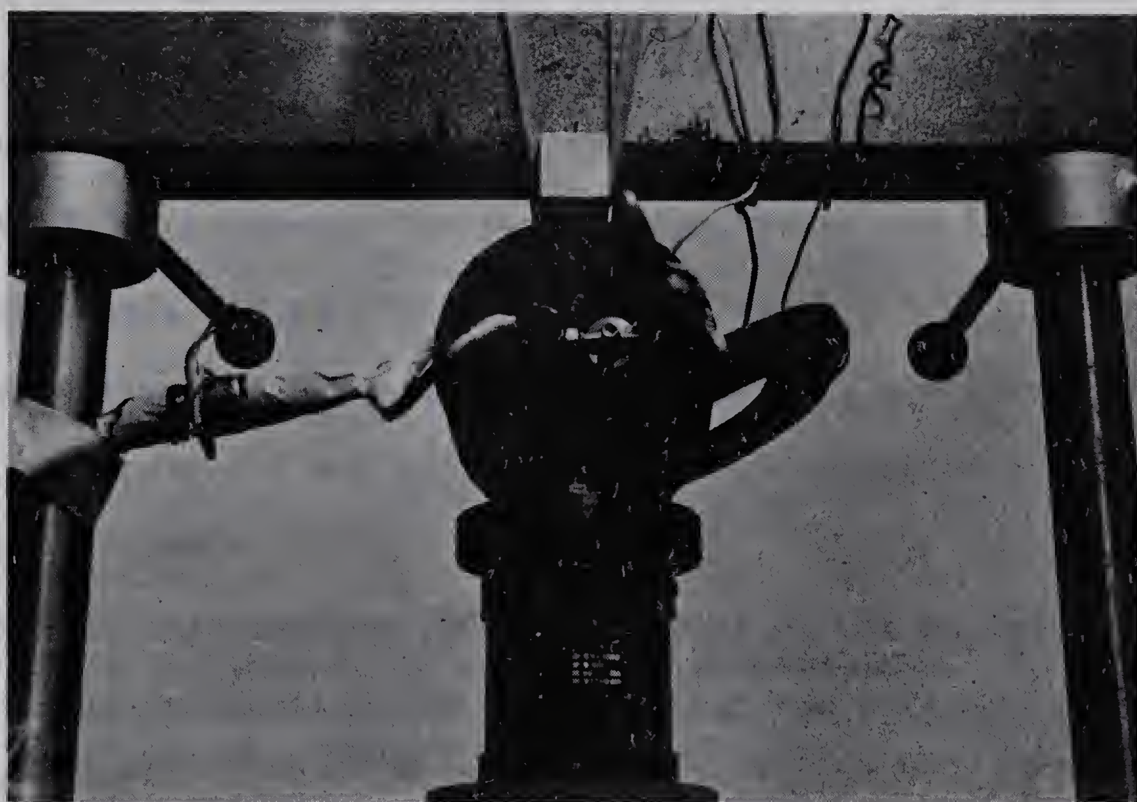


FIG. 9: SPECIMEN READY FOR TESTING

Loading and Recording

1. The compression tester was engaged[1] and a rapid return was made to the recording room, whereupon the recorder servo-motor was turned on and the pen was positioned at the axes intercept. Preliminary experiments had shown that virtually no load or strain was recorded in approximately the first fifteen seconds of loading.
2. If the strain gauge transducer amplifier dial displayed a reading outside the normal range (established by preliminary testing experience), the compression tester was immediately disengaged, and an investigation was made.
3. The specimen number and the series number (later converted to aggregate pit and supply number) was marked on the recorder paper.
4. When the load reached 2000 pounds a timer was engaged. Previous examination had revealed that the rate of plywood compression approached that of the specimen at about 2000 pounds of load. The ensuing time to failure was then a function of the specimen properties.
5. When the specimen was heard to break, the recorder pen was lifted and the timer was disengaged. The recorder servo-motor was turned off.

---

[1] The compression tester was left running during the course of a day's testing. It was necessary to direct a heat lamp (for about one hour) at the motor right-angle drive to facilitate starting at the beginning of a test run.

Termination of Test

1. The failure point was marked on the load/strain curve at the location where the slope first reached zero. This will be discussed in CHAPTER VI.
2. A return was made to the frost room, whereupon the compression tester was disengaged.
3. The broken specimen was examined and any unusual fracture was noted. If the fracture surface passed through a gauge point the test was rejected.
4. The gauge points were detached from the core and coil assemblies and saved for cleaning and re-use. The plywood strips were discarded.
5. Broken specimens were saved and stored on end, for further examination.
6. The loading ram was lowered using the hand wheel.
7. Another test was begun.

A nominal rate of loading setting of 0.06 inches/minute on the compression tester was used for all tests within the program. Christison (1966) found by measurement, that the actual rate of loading was in the order of 0.056 inches/minute.

Specimen Production and Testing Plan

Marshall mix design specimens were used for all the tests in

this program. Replicate specimens of previous 1966 designs were prepared in the standard manner by regular laboratory personnel. Actual field aggregates and asphalt cements were used in the specimen production. Appendix C contains tabulated data on the original Marshall Stability Tests performed. No new Marshall Stability Tests were performed on the replicate specimens tested in this program. Appendix C also contains a summary of available properties of the asphalt cements, used in the preparation of the specimens.

An examination of the broken specimens was made and appropriate observations were noted. Photographs were taken of four random samples from each test series.

CHAPTER V

RESULTS

The results of this testing program and some related data is contained within this chapter. Development of the framework for computer application to data storage and analysis for a continuing study of cracking, could be considered a portion of the results. However, this is not included herein as it is presented in sufficient detail in Chapter III. The associated computer programs and output is contained in Appendix D.

Table I gives an outline of the number of tests used to obtain the curves which will be subsequently presented. Eighteen tests were reported for all aggregate, asphalt cement combinations with the exception of aggregate number 0 and 1. Only thirteen tests were reported for each of these series, due to a lack of specimens.

FIGURES 10 to 13 show the average stress/strain curves and the two standard deviation stress bands for each test series. The vertical distance between the deviation curves gives an indication of the stress dispersions for each test series. Statistically speaking, approximately 95% of the test stress values lie within the bands. Both the average curves and the deviation curves were computed with the aid of the University of Alberta, IBM 7040 computer.

TABLE I

OUTLINE OF NUMBER OF TESTS REPORTED

AGGREGATE NO. / ASPHALT CEMENT SUPPLY NO.	0	1	2	3	4	5	6	7	8	9
1			18	18						18
2						18	18		18	18
3	13	13								18
6					18			18	18	

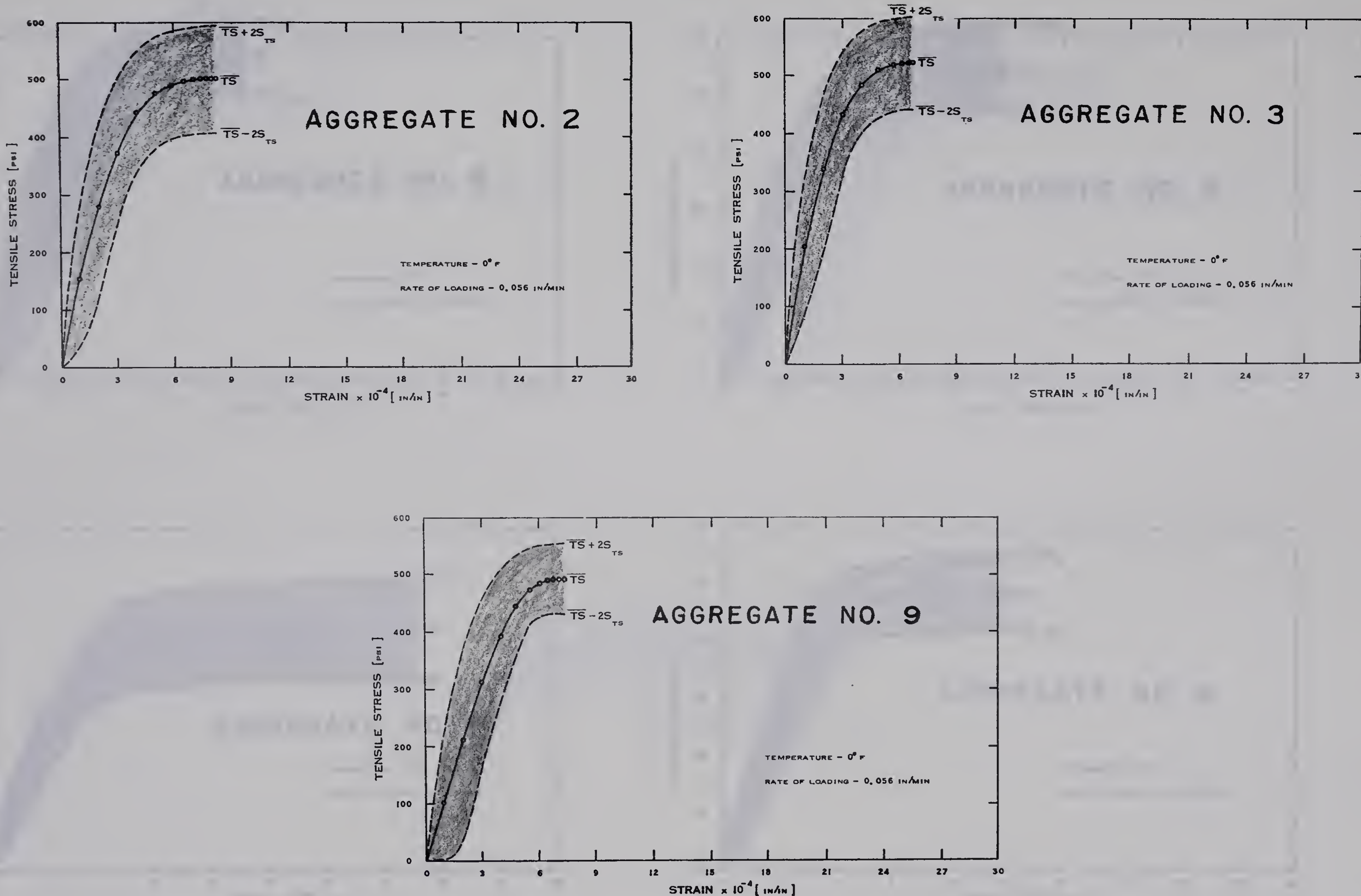


FIG. 10: AVERAGE STRESS/STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. 1

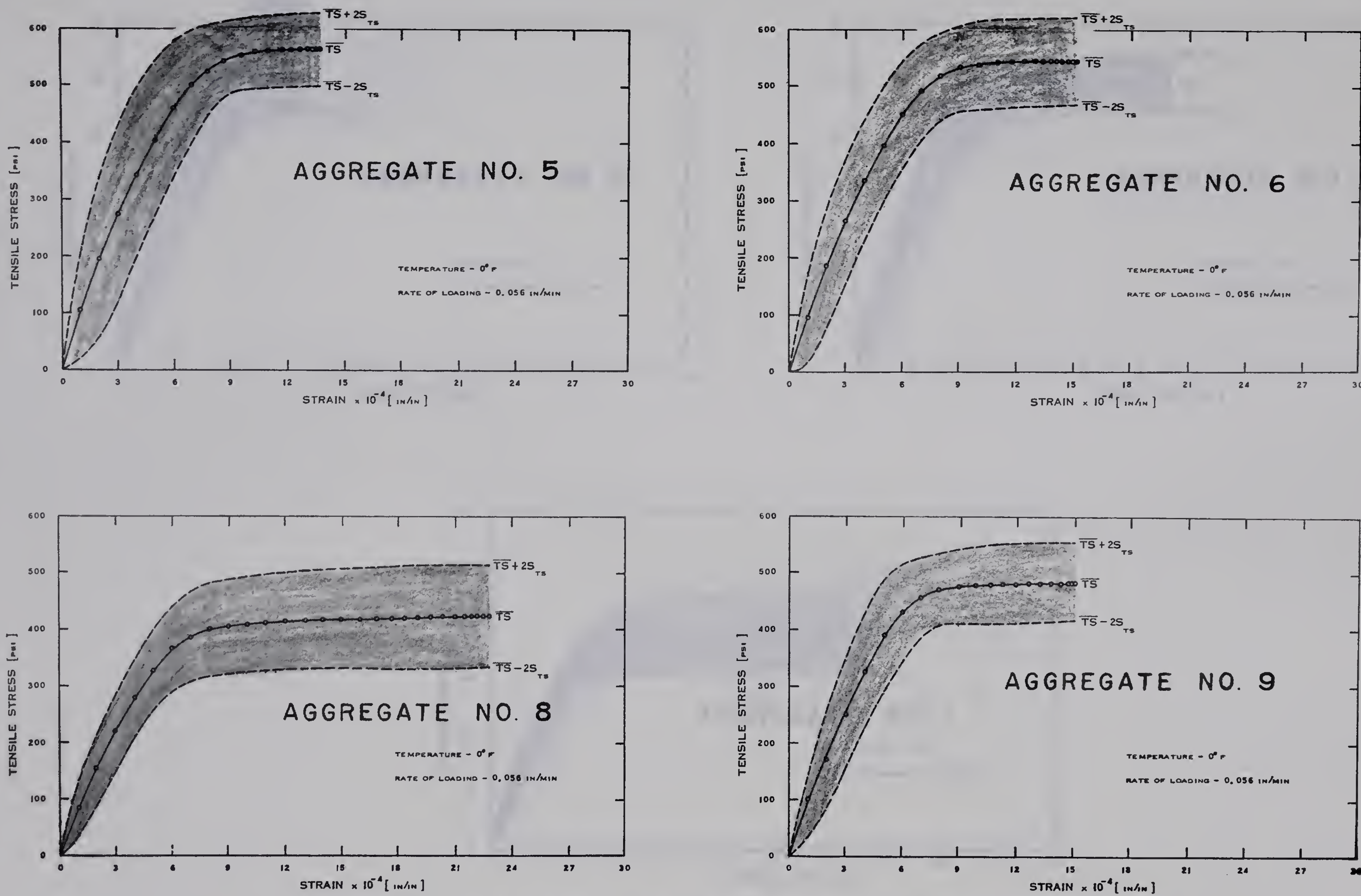


FIG. 11: AVERAGE STRESS/STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. 2

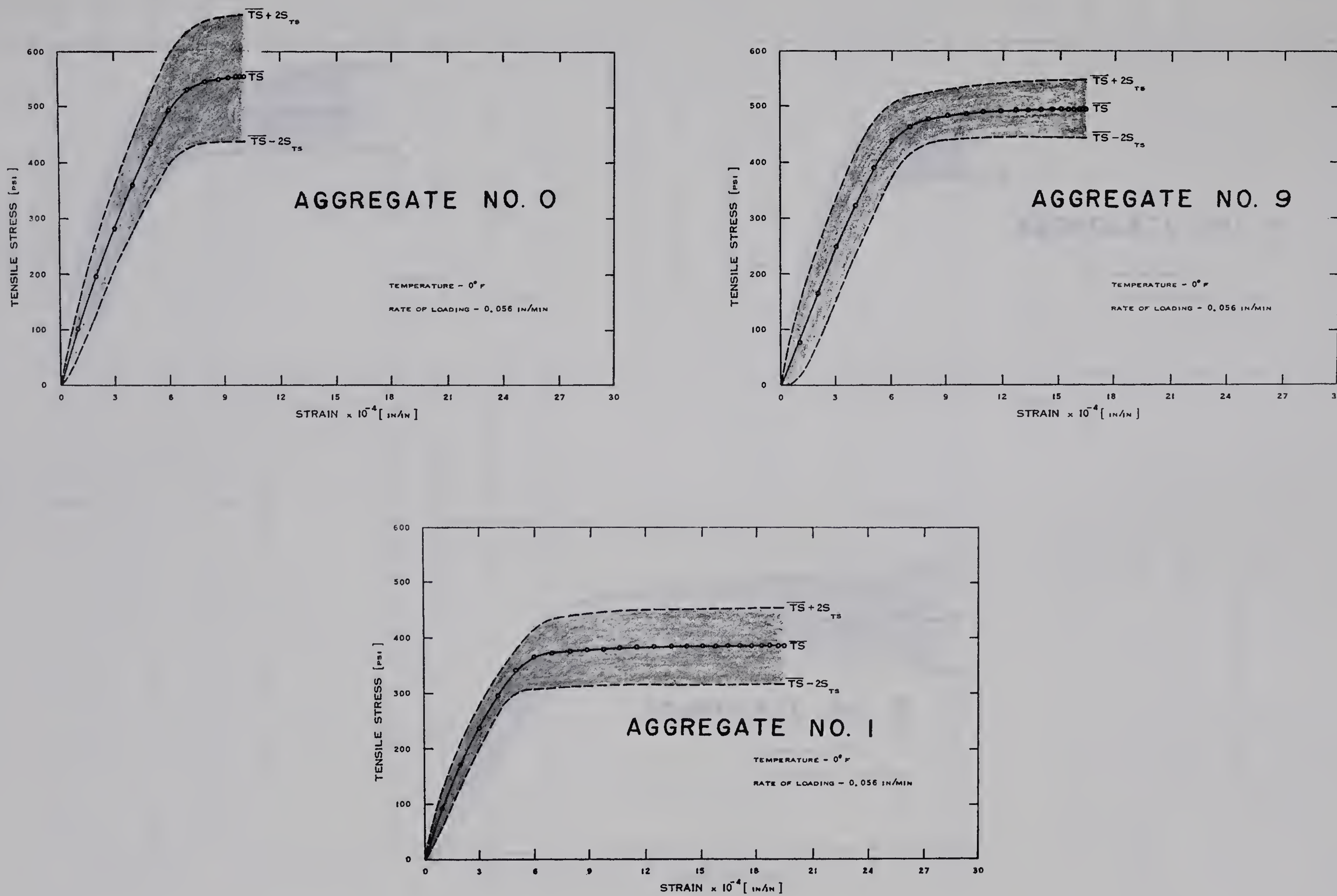


FIG. 12: AVERAGE STRESS/STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. 3

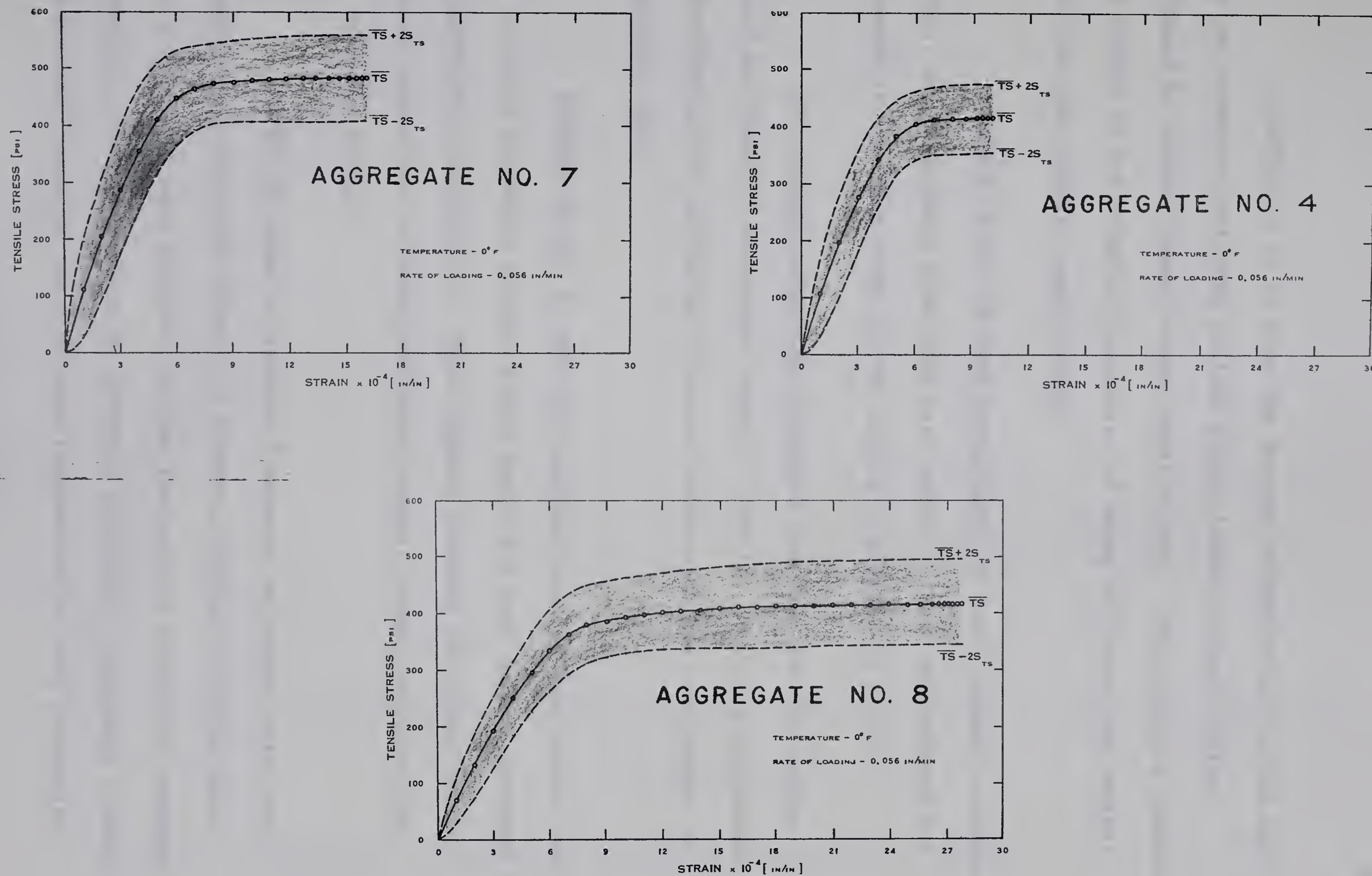


FIG. 13: AVERAGE STRESS/STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. 6

FIGURES 14 to 17 show the average stress/strain curves and the two standard deviation failure strain bands for each series, arranged by asphalt cement supply replications. These figures indicate the effect on the tensile properties, of using different mix designs with the same asphalt cement supply.

FIGURES 18 and 19 show photographs of four randomly selected, broken, half specimens from each test series. These photographs are arranged in the same order as the curves in FIGURES 10 to 13.

The average percentage aggregate fracture for the series tested was found to be between roughly 8 and 15. This was determined by estimating the percentage fracture within each 1/4 inch square of an overlay grid.

FIGURES 20 and 21 show the average stress/strain curves and two standard deviation failure strain bands for each series, arranged by aggregate replications. These figures indicate the effect on the tensile properties, of using different asphalt cement supplies with the same mix design.

FIGURE 22 shows a cracking frequency bar chart, which was prepared using Research Council of Alberta, Highways Division data. Mean cracks/mile were plotted, so that the various lengths of pavement considered at each age would be properly weighted. The number within each bar indicates the total mileage represented by that particular

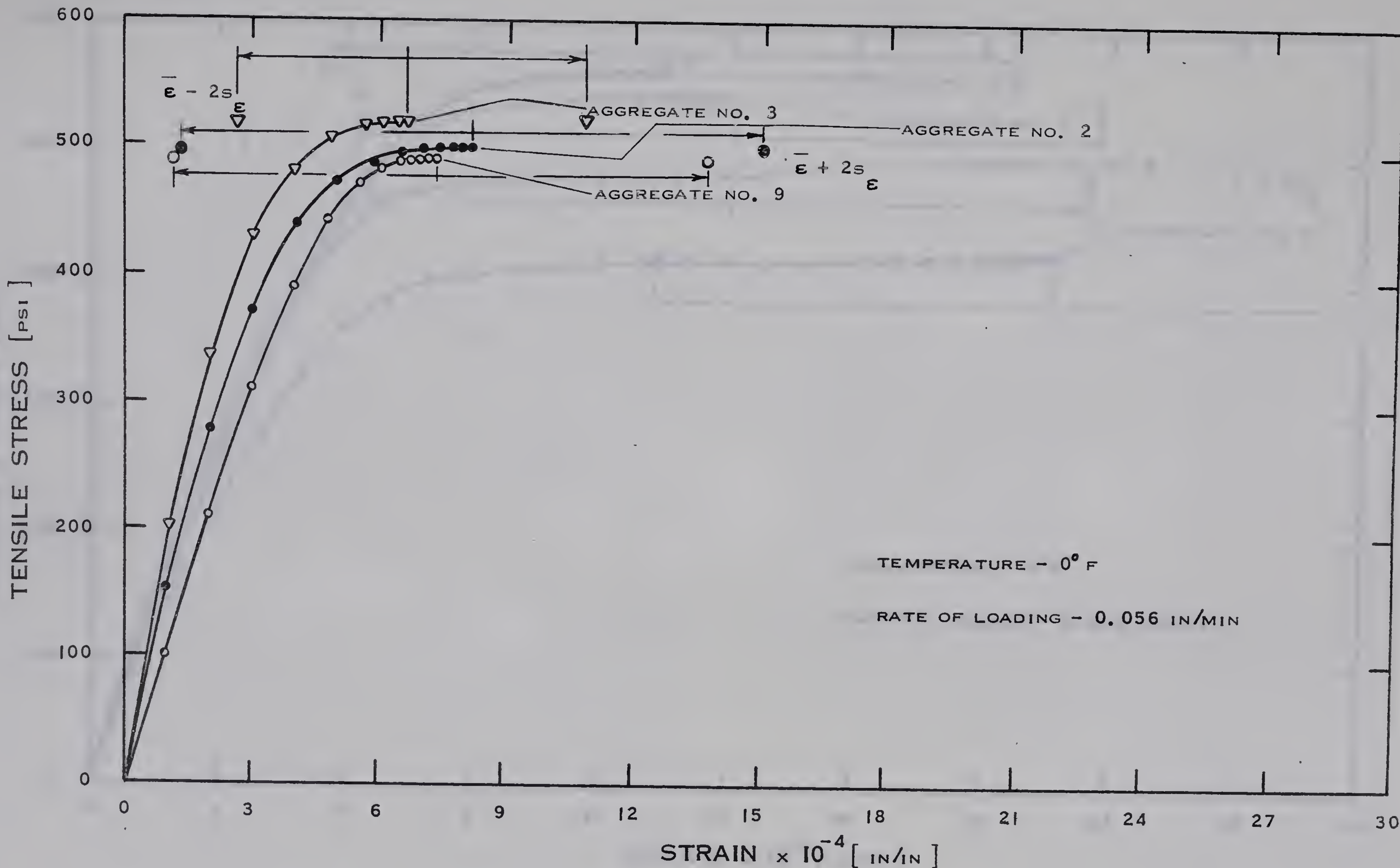
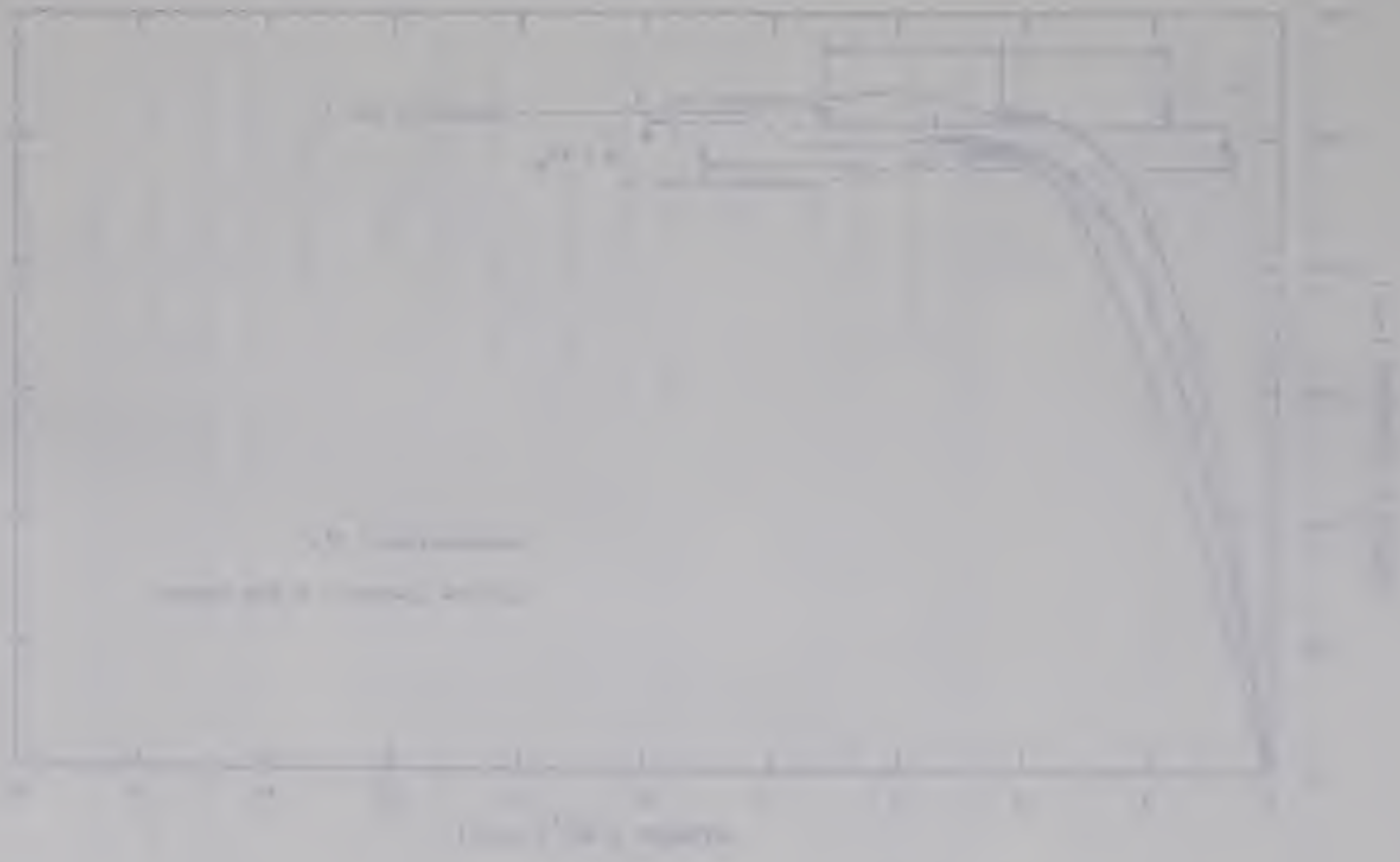


FIG. 14 : AVERAGE STRESS / STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. I



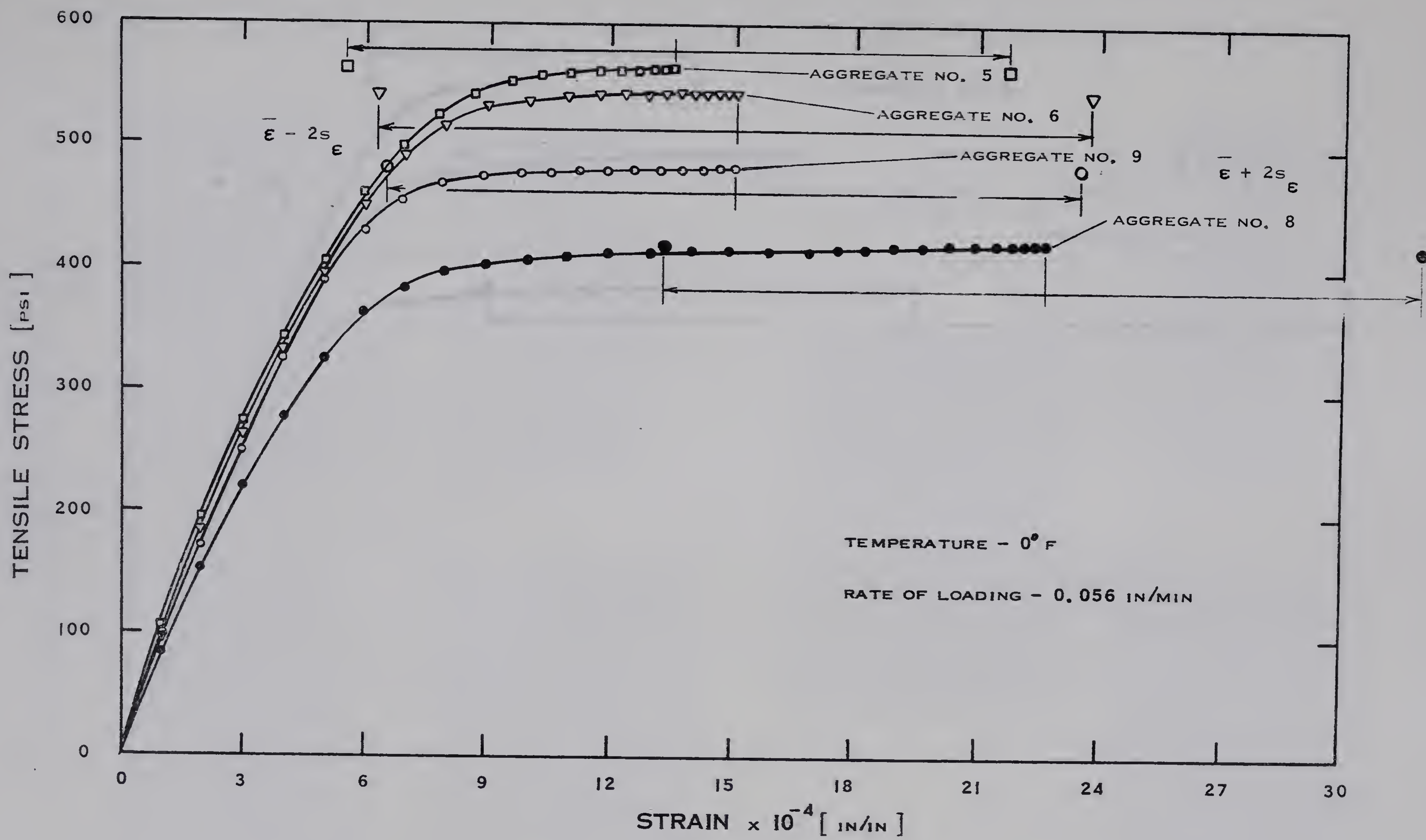
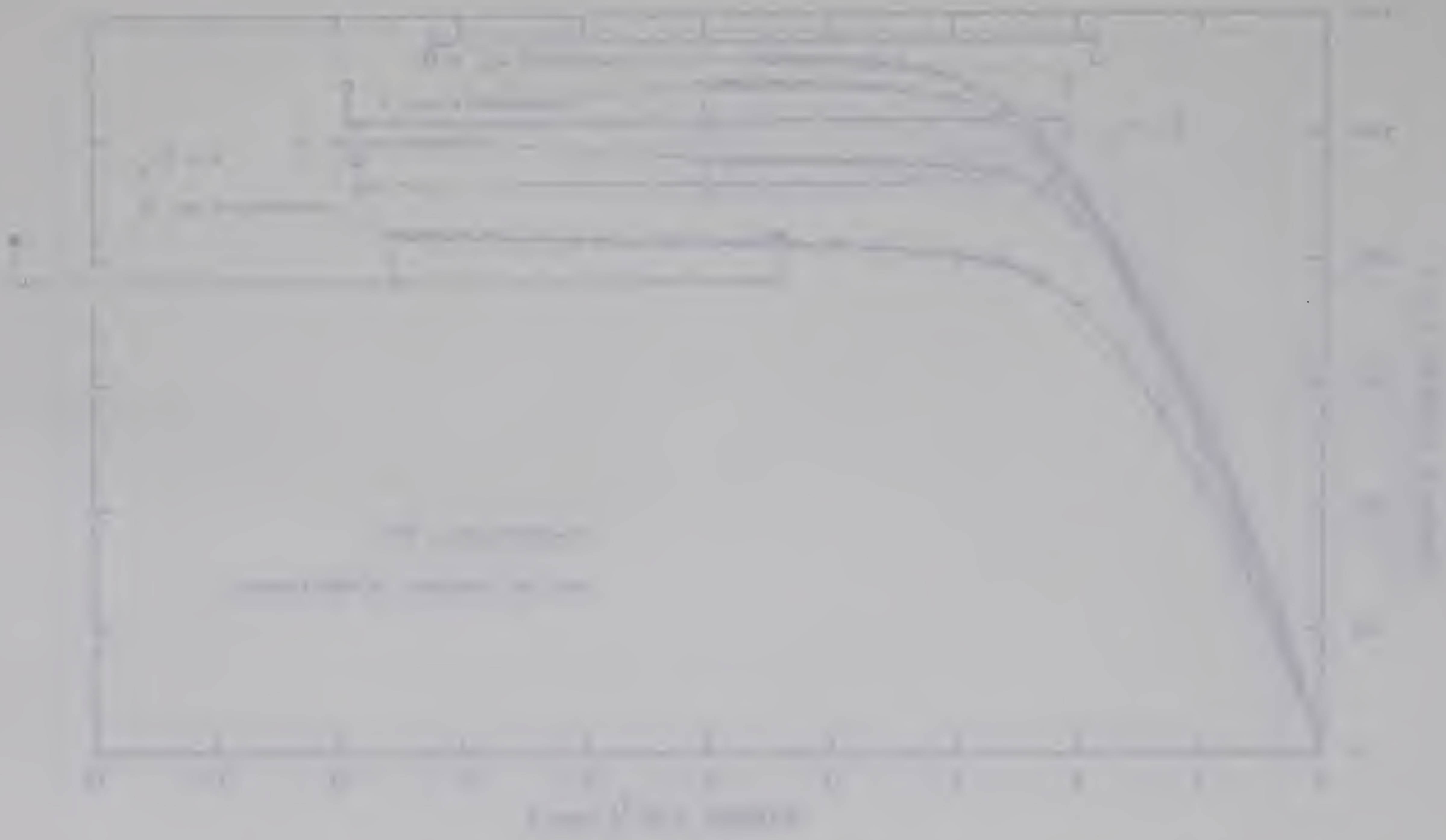


FIG. 15: AVERAGE STRESS / STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. 2



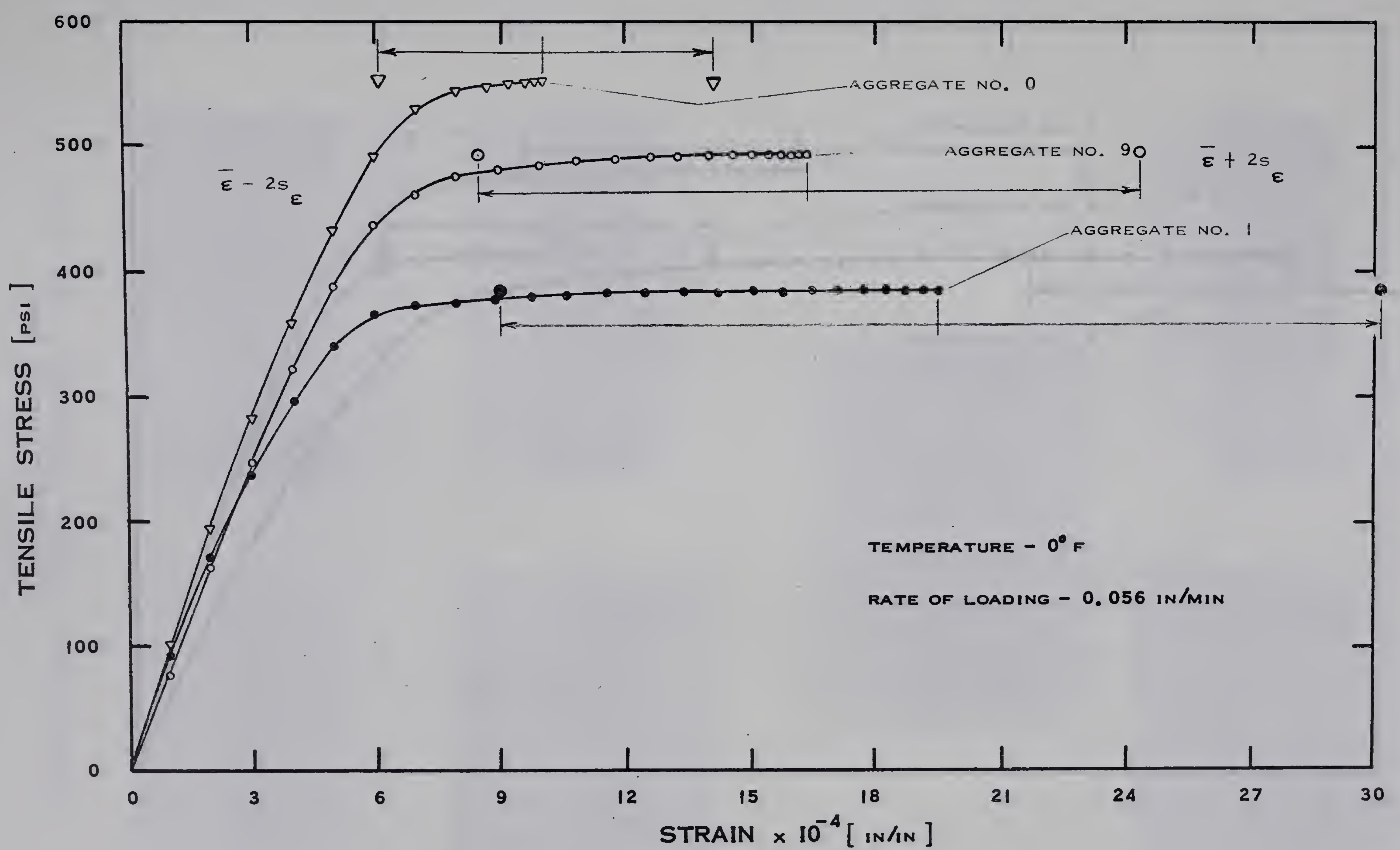
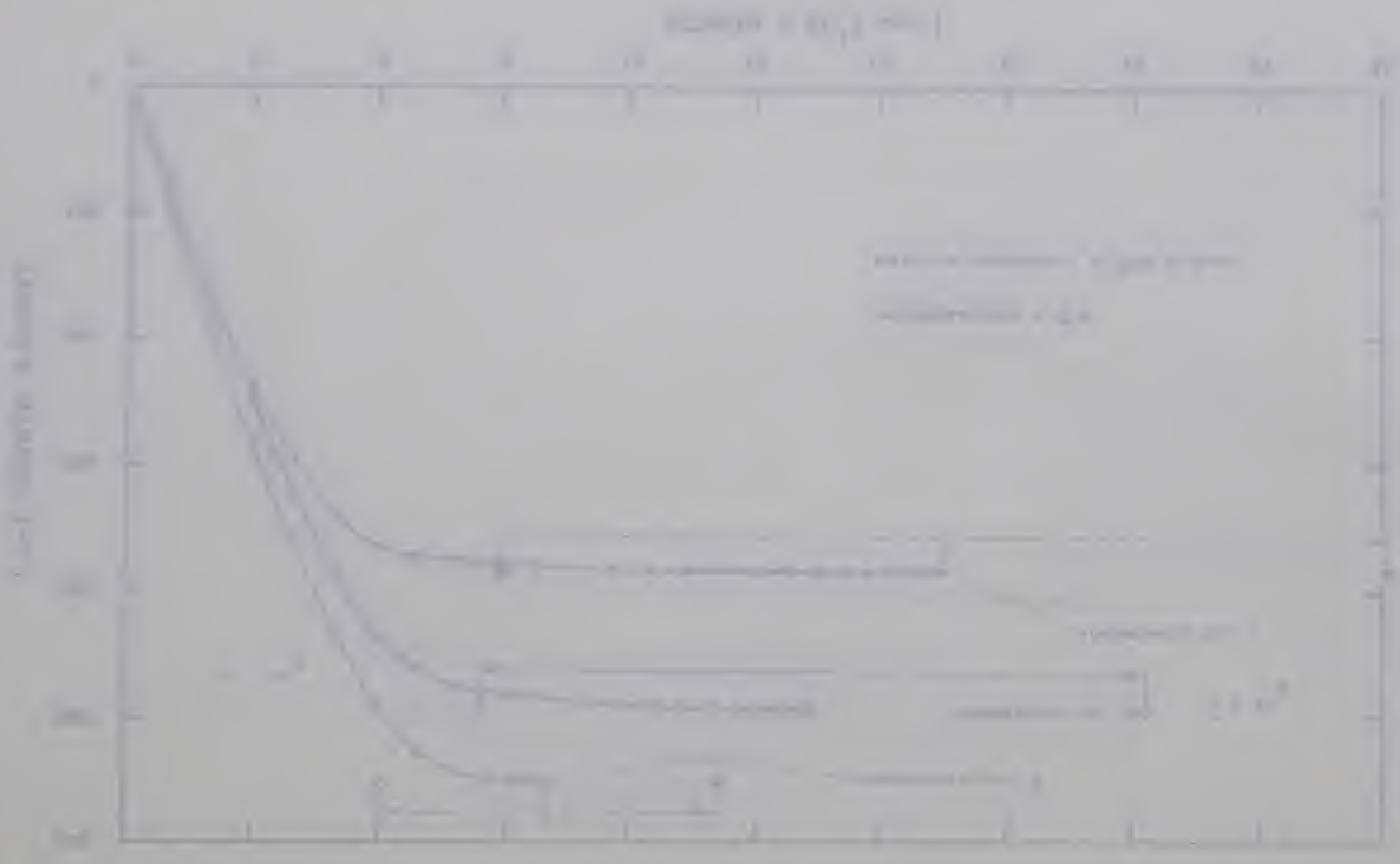


FIG. 16 : AVERAGE STRESS / STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. 3



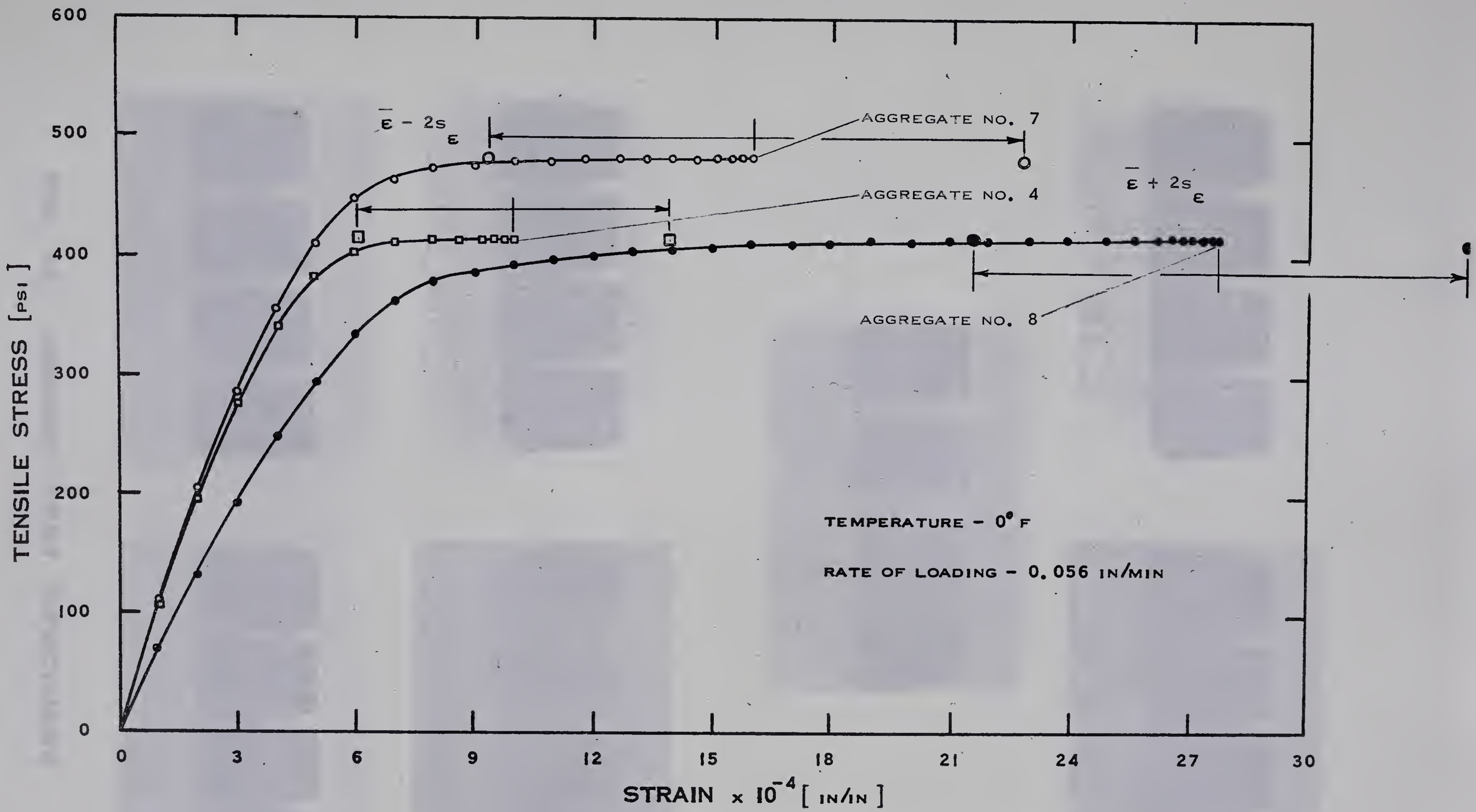


FIG. 17 : AVERAGE STRESS / STRAIN CURVES FOR ASPHALT CEMENT SUPPLY NO. 6

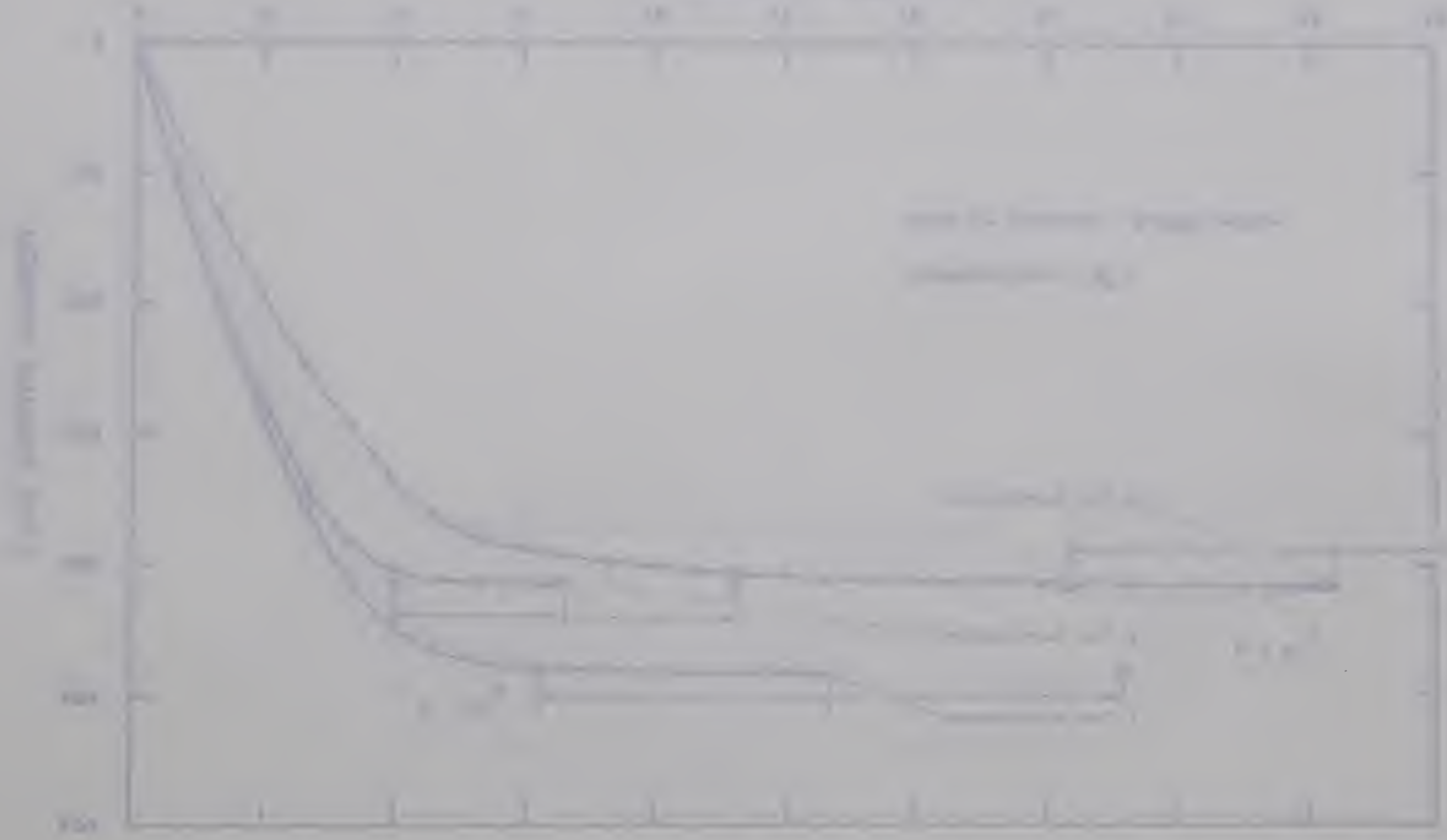


FIG. 18: BROKEN TEST SPECIMENS

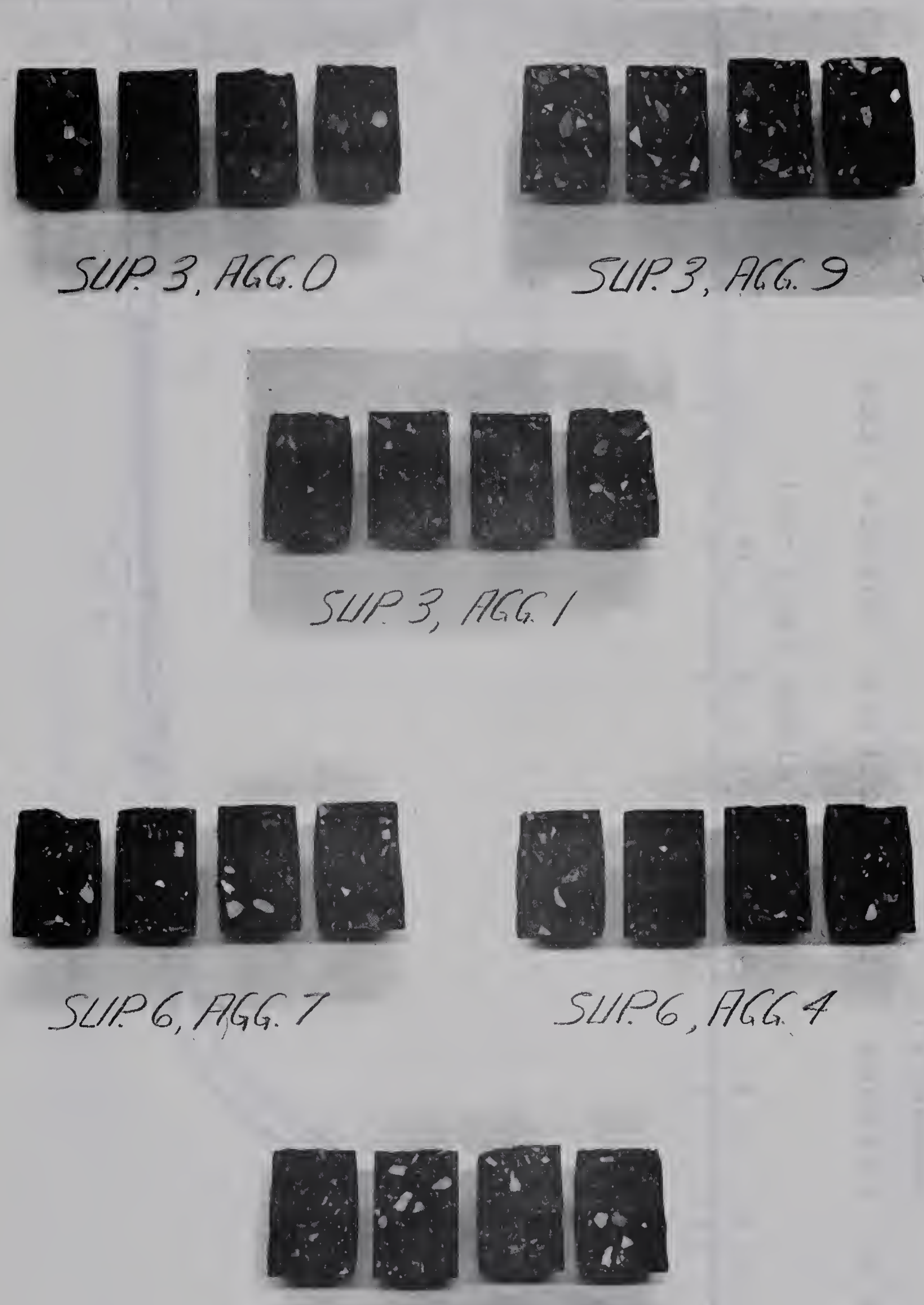


FIG. 19: BROKEN TEST SPECIMENS

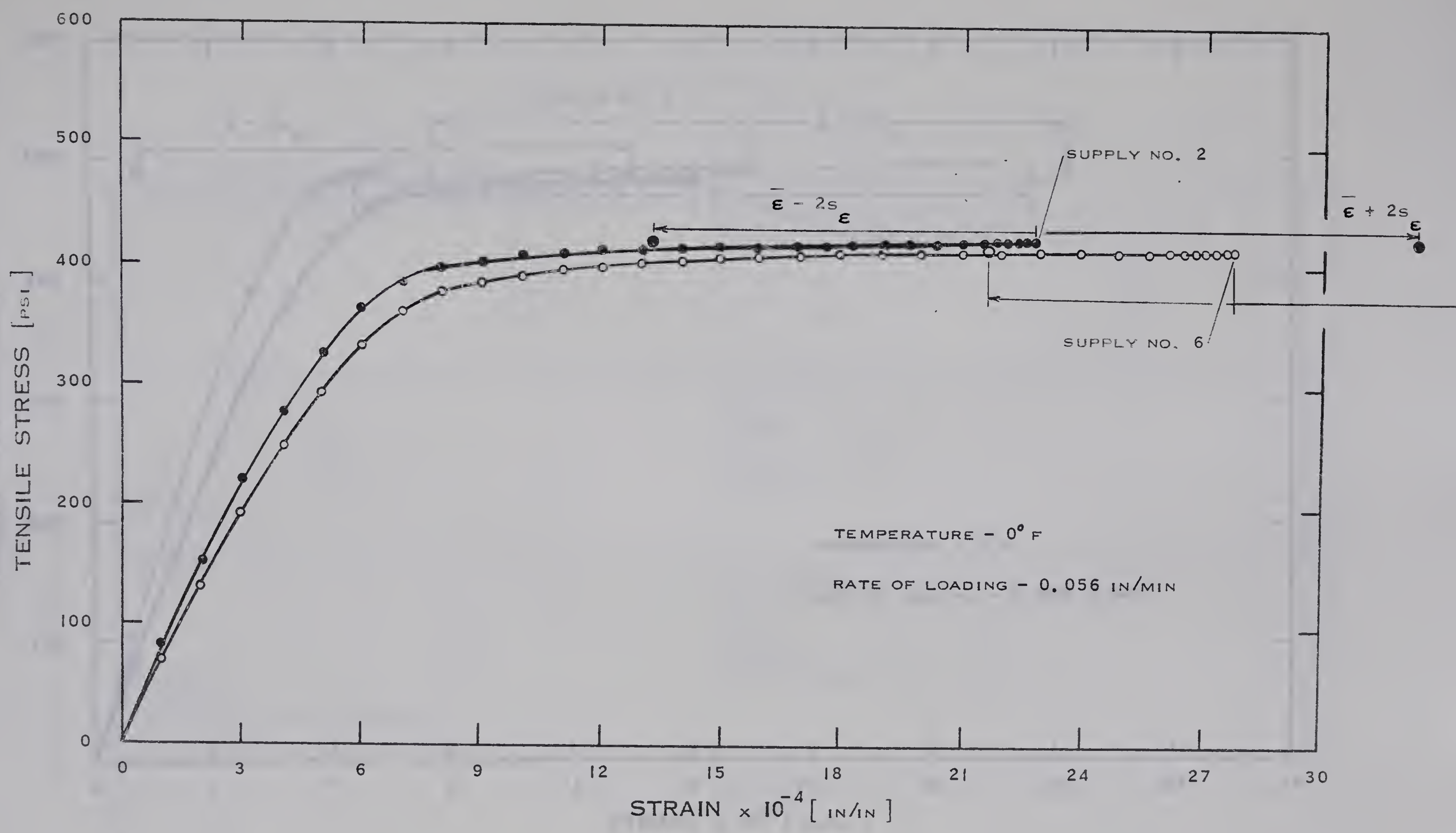
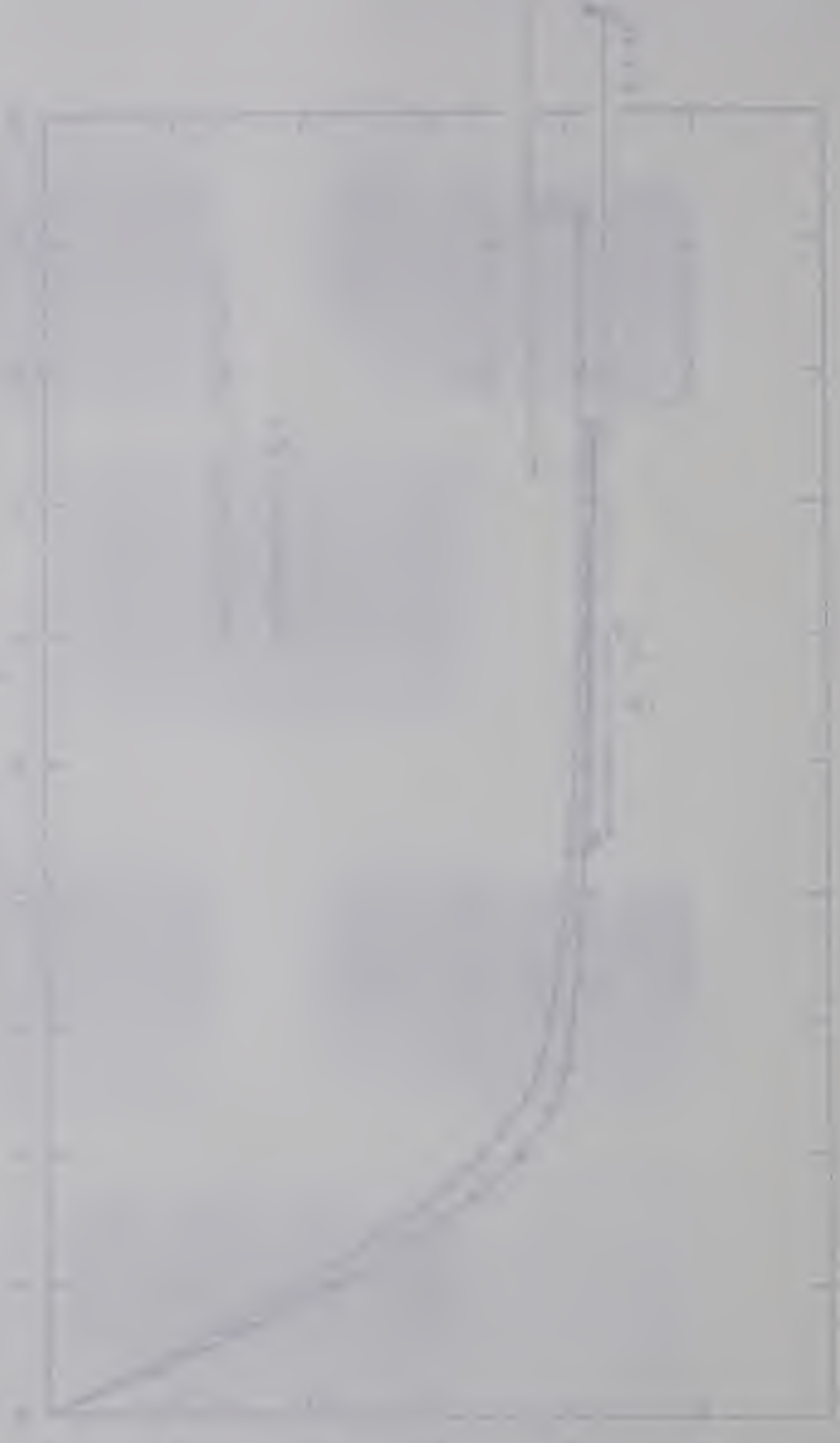


FIG. 20: AVERAGE STRESS / STRAIN CURVES FOR AGGREGATE NO. 8



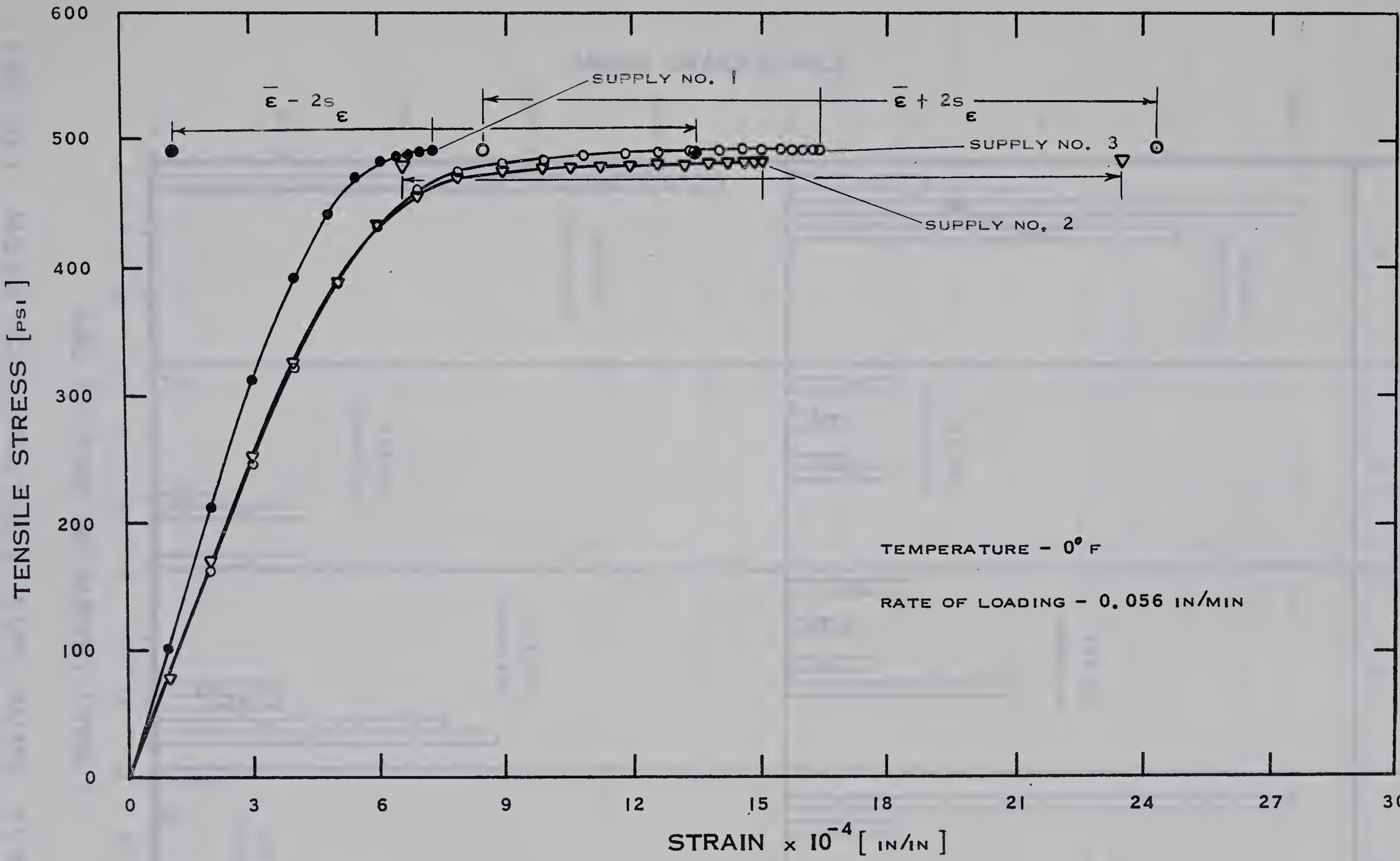
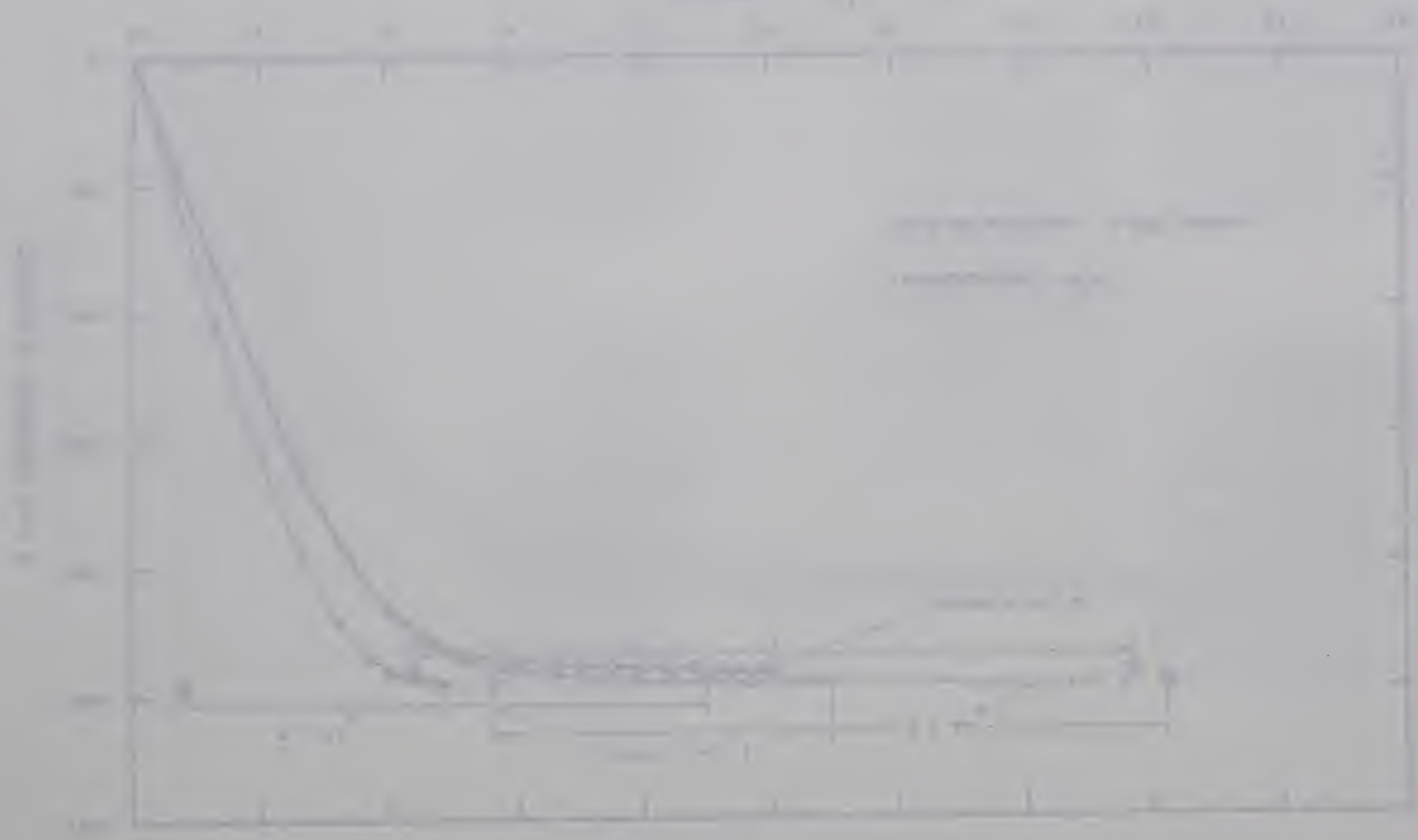


FIG. 21 : AVERAGE STRESS / STRAIN CURVES FOR AGGREGATE NO. 9



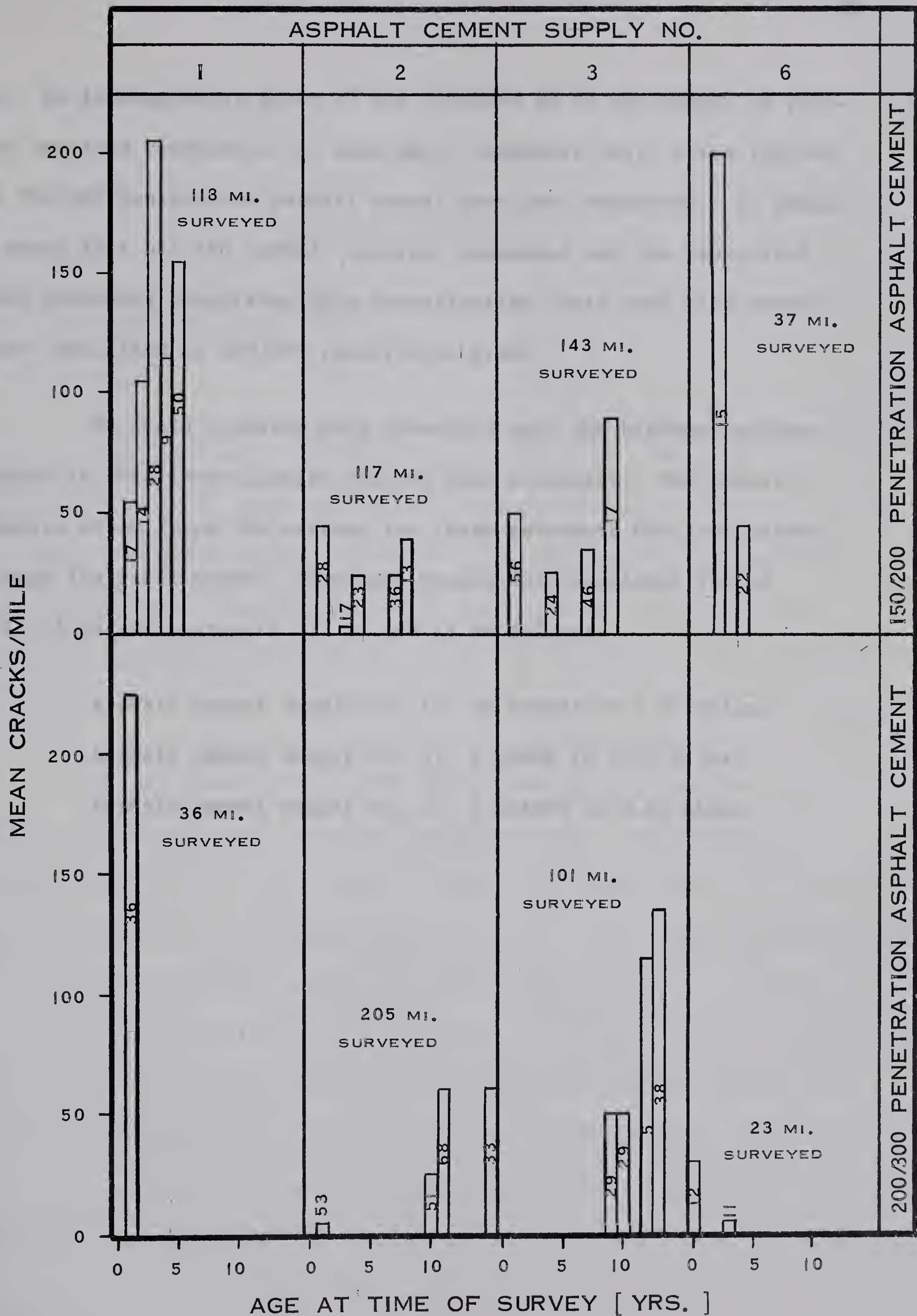


FIG. 22 : MEAN CRACKS/MILE FOR SOME ALBERTA HIGHWAY SECTIONS AT VARIOUS AGES.
[PREPARED FROM RESEARCH COUNCIL OF ALTA. DATA]

bar. No indication is given of the location or of the number of pavement sections represented by each bar. Pavements built using 150/200 and 200/300 penetration asphalt cement have been separated. It should be noted that all the asphalt concrete specimens and the associated field pavements comprising this investigation, were made with asphalt cement specified as 200/300 penetration grade.

No field cracking data connected with the highway sections studied in this investigation has yet been presented. The asphalt concrete which forms the surface for these pavements has just passed through its first winter. The most recent data available (as of April 3) is for aggregate no. 9, and is as follows:

Asphalt cement supply no. 1; 24 cracks in 7.65 miles.

Asphalt cement supply no. 2; 1 crack in 9.02 miles.

Asphalt cement supply no. 3; 4 cracks in 8.63 miles.

CHAPTER VI

DISCUSSION OF RESULTS

Influence of Procedure on Results

Calibration

Calibration of the strain gauges was a very delicate operation because of the small magnitude of the calibration range. Even with the specially constructed gauge calibration jig, extreme care in manipulation was required. Despite the sensitive nature of the calibration procedure, reproducibility of the calibration curves was quite satisfactory.

It was necessary that the two strain gauges used for testing were well matched, since the total deformation was considered to be proportional to the average strain. With this series system, wherein the two signals due to deformations are additive, any marked differences in the gauges would have resulted in meaningless readings. The manufacturer's rated sensitivity did not appear to be sufficiently accurate for the purposes of this investigation. All three gauges checked had significantly different calibration curves. By choosing the two gauges with the most closely matched curves, the error due to sensitivity difference was minimized.

Testing

Satisfactory attachment of the gauge points to the specimens was a problem, particularly in the early stages of this investigation. The gauge points often slipped from their proper positions or did not have sufficient bond strength to resist being knocked off during attachment of the strain gauges. Proper coating of the gauge points with the optimum amount of asphalt cement required some experimentation. Application of a firm pressure to the gauge points during attachment was required. Immediate chilling was necessary to obviate flow within the bonding asphalt film. Some flow must have occurred in all instances, as the specimens were stored on their sides. However, in a properly prepared specimen there was no noticeable movement of the gauge points. Thus any error introduced into the strain readings was considered negligible.

The testing in this investigation was performed by one man. Assistance was obtained for preparation of the specimens for testing and for the final calibration of the strain gauges at $0^{\circ}F$. The testing procedure developed was not difficult. No special knowledge was required by the operator once the procedure was established. A certain amount of manual dexterity was required for the positioning of the specimen and for the attachment of the strain gauges. An experienced operator can conduct a complete test in fifteen minutes.

Specimen Production

Since no Marshall Stability Tests were conducted on the replicate specimens used in this investigation, it was necessary to assume that the original Marshall design data was representative. This was not a likely source of significant error, as the aggregates taken from the same pits were used in preparation of the specimens. The difference between the properties of the specimens tested and the field asphalt concrete could be substantial. Since the field properties were not determined in this investigation, caution should be exercised if any direct application of these test results is desired.

Computer Application

General

It was found in this investigation that manual acquisition, sorting and analysis of background data was difficult. A computer data storage and analysis system similar to that which was outlined in Chapter III would certainly produce a more consistent set of data, which could be easily retrieved and/or analyzed. By making extensions to the framework outlined, other areas within the materials field could be served. Some possible areas of extension are to:

1. The analysis of load carrying capabilities of pavements for determination of loading restrictions and for the determination of required strengthening.

2. The analysis of quality control data for setting realistic within job specifications.
3. The analysis of pavement serviceability from objective field measurements, and the estimation of the time of terminal serviceability.

In addition, other construction records which would be useful for future reference or study, could be stored within a computer data system.

Tensile Splitting Test

After the failure strains have been marked on the test curves, a technician need only punch the pertinent information from the curves and from the measurement records onto data cards. All the calculations are done by the computer. The average curve and the statistical parameters for each test series can then be plotted. If a large number of test series were being conducted it might be advantageous to have the plotting done on an autoplotter. With this computer method of analysis the engineer can devote his time to the examination of the results. The need for supervising and checking calculations is virtually eliminated.

Results

Experimental Errors

No allowance was made for experimental errors in securing the average curves from the tests performed. The load cell was found to diverge from linearity in the lower range (to approximately

200 p.s.i.). The effect of this non-linearity would be to cause the initial portions of the curves to be somewhat straighter. Since in this investigation the elastic portion of the stress/strain curves was not considered, no correction was made. The difference was not great enough to render the curves obtained unrepresentative. Comparative values within this investigation are still quite valid.

The errors associated with the strain measurements were too small to be considered as significant. Any measurement error due to temperature change of the gauges induced by handling was not considered. Since about the same amount of handling was involved in each test, any error introduced would be consistent.

Determination of Failure Strain

The gauges were wired in series and were of almost equal sensitivity, so the sum of the electrical output was proportional to twice the average deformation on the ends of a specimen. Preliminary testing indicated that deformations on both ends of a specimen were not always equal. This could be due to the non-homogeneity of the material within a specimen and/or to an unbalance in the loading over the thickness of a specimen. By measuring deformations at both ends, the dispersions of the failure strains should have been reduced. Although Christison (1966) tested three series made with aggregate no. 9, it was not possible to determine whether the dispersions were reduced. He measured deformation at only one end of a specimen, but was forced to extrapolate

the failure strain on a time basis to obviate damage to the optical strain gauge. Even with the method used in this investigation it is assumed that the average failure strain as measured at the ends of a specimen is representative of the strain over the entire thickness.

The failure strain referred to throughout this thesis, is the sum of the horizontal tensile strain due to the tensile stress and the horizontal tensile strain due to the Poisson's Ratio effect. Christison '1966) considered only the strain due to the tensile stress.

It was necessary to adopt a criterion for determination of the failure strain on the test curves. Preliminary testing had indicated that no distinct failure point could be observed with most test series. The failure strain in this investigation was taken as the point at which the slope of the load/strain curve first reached zero. This was the first incidence of peak load. The reason for establishing this criterion was that any differences between series with different asphalt cement supplies would be minimized. Series exhibiting larger strains actually continued to deform appreciably before splitting, after the criterion failure strain had been reached. Series exhibiting smaller strains split almost immediately after reaching the criterion failure strain. Thus any tests for the significance of difference of the means of test series could be considered quite valid.

Importance of Failure Strain

It was stated in Chapter II, that in the field the induced tensile strain was considered to be quite important. Of the parameters obtainable from the tensile splitting test, the failure strain appears to best illustrate differences in tensile behavior between test series. Collating these two factors, it would seem that what is important in the field is also important in the test. The subsequent evaluation of the test results will help to reveal whether the average test failure strain is a substantially significant indicator of differences between series.

Dispersion of Test Results

FIGURES 10 to 13 indicate that the stress dispersions at the failure stress level were not markedly different. Aggregate no. 0 and aggregate no. 9 in FIGURE 12 displayed respectively the greatest and the least dispersion of the 13 test series. It should be noted that there were only 13 tests in the aggregate no. 0 series. The widths of the 95% dispersion bands ranged from 228 to 105 p.s.i. Some of the dispersions in the initial range of the curves were proportionally larger than at the failure stress level. The substantial dispersions indicate that the Marshall specimens were certainly far from uniform. Prior visual examination of the specimens had revealed this non-uniformity. However, during the course of the testing program no effort was made to select a uniform series of specimens. A realistic representation

of the results which could be expected under routine test conditions was desired.

Dispersions of the failure strains were all large. Coefficients of variation ranged from 42% to 11%. Dispersions of this magnitude appear to be too large to be accounted for by material variability alone. Perhaps the choice of a criterion failure strain could be responsible for a portion of the dispersion. Since this criterion was chosen only for the sake of facilitating comparisons between test series, there is no valid reason to believe that the dispersion of the criterion failure strain should be the same as the dispersion of the "true" failure strain.

Within Supply Variations

The three mix designs that utilized supply no. 1 asphalt cement (FIGURE 14) did not display any significant difference in failure strain at the 5% level, when tested using the "t" test. Failure strains of these three series were the smallest of all the series tested.

Of the four mix designs that utilized supply no. 2 asphalt cement (FIGURE 15), only the failure strain of the aggregate no. 8 mix was significantly different at the 5% level. It was also significant at the 1% level. This mix contained only about 6% of minus number 200 sieve material, which resulted in a relatively low stability.

The three mix designs that utilized supply no. 3 asphalt cement (FIGURE 16) exhibited fairly distinct differences. Aggregate no. 0 mix and aggregate no. 9 mix failure strains were significantly different at the 1% level. Aggregate no. 9 and aggregate no. 1 mix were significantly different at the 10% level. Again the mix with the largest failure strain contained the least amount of fines, and had the lowest stability.

The three mix designs that utilized supply no. 6 asphalt cement (FIGURE 17) all had failure strains which were significantly different at the 1% level. Attributing the differences only to mix design may not be valid in this case. The properties of this asphalt cement have been found to be rather variable. However, the mix with the least fines and the lowest stability again was associated with the largest failure strain.

From a consideration of the above paragraphs, it appears that poor Marshall Stability characteristics (at $140^{\circ}F$) are associated with large failure strains (at $0^{\circ}F$). Conversely, in the case of supply no. 2, 3 and 6 the high fines, high stability mixes display the poorest low temperature strains. The effect of a high fines content may be twofold. First, the stability of the mix is high and thus would be expected to be more brittle at low temperatures. Second, the aggregate particles are more likely to be dusty or coated with fine material, than would be the case with a low fines content. The second

factor may tend to cause some decrease in the strain capability due to a loss of bond. The previous discussion does indicate that a method for evaluating the low temperature cracking performance of asphalt concrete is definitely needed. The Marshall design method, although certainly required, does tend to work against satisfactory low temperature performance.

Within Mix Design Variations

The only difference between the mixes which are represented by the curves in FIGURE 20 is the asphalt cement supply. Failure strains for the two mixes shown were significantly different at the 1% level. However, on a relative basis the difference in failure strain was not too great. Both series exhibit very high failure strains. It should be noted that the failure stresses were almost equal.

Of the mixes represented by the curves in FIGURE 21, the supply no. 2 and 3 failure strains were not significantly different. The difference between supply no. 1 and supply no. 2 or 3 was significant at the 1% level. Both supply no. 2 and 3 exhibited about double the strain capability of supply no. 1. These results agree with those of Christison (1966) who also tested Marshall specimens having the same properties. The values obtained in this investigation for the failure strains of the supply no. 1, 2 and 3 mixes were respectively 0.00074, 0.00151 and 0.00165 in./in. If Christison's values are doubled (one-half of the failure strain was taken as being due to the Poisson's Ratio effect), the values 0.00080,

0.00134 and 0.00122 are obtained. Considering the fact that Christison extrapolated the failure strain values on a time basis, the agreement is quite good.

Christison's (1966) average failure stresses were about 10% higher than those obtained in this investigation. Possibly the use of a different size of loading strips (1/4 x 1/2 x 3 inches) by Christison might account for a substantial portion of the difference. It should again be noted that all three mixes tested (FIGURE 21) exhibited almost identical failure stresses.

From a consideration of the curves shown in FIGURES 20 and 21, it appears that the failure stress in the tensile splitting test is a function of the aggregate used in the mix. The failure strain appears to be primarily a function of the asphalt cement supply used in the mix. It is apparent that at the rate of loading and test temperature used, there are very marked differences in strain capabilities of similar mixes which utilized different asphalt cement supplies. This supports the concept of consideration of strain which was advanced in Chapter II. Behavior of asphalt concrete under field conditions would be expected to be analogous. An examination of some field cracking data is necessary to determine whether test failure strain is indicative of cracking performance.

Correlation with Cracking Data

The cracking frequencies shown in FIGURE 22, for asphalt

concretes made with supply no. 1, 2 and 3, 150/200 penetration asphalt cement can be sensibly compared. Over 100 surveyed miles are available for each supply. Supply no. 1 pavements definitely have a greater cracking frequency than either supply no. 2 or 3. The average failure strains for the series tested within each asphalt cement supply, were in the reverse order to the cracking frequencies. That is, supply no. 1 had the lowest failure strain, supply no. 3 had the next highest and supply no. 2 had the highest. The validity of taking averages of only 3 and 4 test series as a basis for such a direct comparison is questionable. However, it is certain that there is a rough correlation between test failure strain and field cracking frequency. A low test failure strain is usually indicative of poor cracking performance.

The same correlation between failure strain and cracking frequency is evident from a consideration of the 200/300 penetration asphalt cement cracking data. It should be noted that supply no. 1 is represented by only two pavement sections which have a total length of 36 miles. The meagre data presented for the aggregate no. 9 mixes (at the end of Chapter V) indicates that supply no. 1 asphalt concrete exhibited the highest cracking frequency. Thus it can only be said, that on the basis of the data available to date. asphalt concrete made with supply no. 1, 200/300 penetration asphalt cement displays on the average the highest cracking frequency.

The data presented in FIGURE 22 does not give any indication

that the use of 200/300 penetration asphalt cement does reduce the amount of cracking. Relative magnitudes of cracking frequencies between supplies are similar for both penetrations. Consequently, whether the results of this investigation are compared with 150/200 or 200/300 cracking frequencies, does not appear to matter.

Summary and Additional Considerations

No serious problems were encountered in developing a practical method of conducting the tensile splitting test. The analysis of the automatically plotted test curves was done by an electronic computer. A framework for computer data storage and analysis for a continuing study of cracking was also developed.

A criterion failure strain was adopted which tended to minimize the differences between test series. Even so, significant differences in failure strain were obtainable.

The need for supplementing the present Marshall design procedure with a low temperature tension test is apparent. The X-Y recorder and associated electronic equipment required for the tensile splitting test could serve a dual purpose. Kofalt and Sandvig (1967) were able to determine additional useful information from the Marshall Stability Test by using automatic recording.

The findings of previous investigators with respect to the

importance of asphalt cement supply on the tensile properties of asphalt concrete and on the occurrence of cracking, were confirmed. A substantial amount of test data is now available to support the validity of the tensile splitting test for predicting cracking performance trends. On this basis there is a possibility that the test could be used as a supplementary specification for asphalt cement. In this connection, it has been suggested by various investigators that specifications for asphalt cement be based on the performance of the mix.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The general purpose of this investigation was to develop and substantiate a design method for the evaluation of thermal cracking performance of asphalt concrete. The extent of the achievement of this purpose will be given in the subsequently presented conclusions and recommendations of this investigation.

Conclusions

1. A method of conducting the tensile splitting test on asphalt concrete Marshall specimens has been developed which is considered sufficiently practical to be used as a routine test.

2. The framework for a computer data storage and analysis system for a continuing study of the cracking problem has been developed. Programs for only two of the six phases outlined were actually written.

3. Previous conclusions regarding the effect of asphalt cement supply on the tensile properties of a given mix and on the occurrence of cracking, have been substantiated. The occurrence of cracking was found to increase as the tensile failure strain decreased. Failure strain was found to be

a function of the asphalt cement supply when the same aggregate was used. The failure strain was considered to be the most significant parameter resulting from the tensile splitting test because:

a. Any differences between test series were readily discernible.
b. In the field pavements it is plausible that cracking is due to induced tensile strain. Thus resistance to cracking is necessarily a function of the strain capability of the asphalt concrete.
c. A limiting test failure strain could be established for design purposes.

4. It does not appear to be possible to compensate for very poor tensile strain characteristics by modifications in mix design. There is some indication that mixes which have desirable Marshall Stability Test properties, have undesirable tensile splitting test properties.

5. The tensile splitting test method developed is considered to be a valid design method for asphalt concrete used in colder climates.

Recommendations

1. The adoption of the tensile splitting test method to supplement the present design procedure for asphalt concrete pavements should be seriously considered (for colder regions).

2. A standard tensile splitting test method could be used to evaluate asphalt cements at low temperatures for specification purposes.

Recommendations for Further Study

1. The frequency of cracking on the highway sections investigated should be correlated with the test failure strains obtained.

2. An approximate limiting test failure strain should be determined which would preclude unsatisfactory cracking performance under a given set of environmental conditions. It may be possible to determine this from the highway sections studied.

3. Investigation to secure an understanding of the mechanics of crack formation should be continued.

4. Further investigation should be conducted to determine what property or properties of asphalt cement are responsible for poor tensile strain characteristics.

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APPENDIX A

DESCRIPTION OF TESTING APPARATUS

- Gauge Point Jig
- Strain Gauges and Associated Equipment
- Strain Gauge Calibration Jig
- Loading and Load Measurement Apparatus
- Recording Apparatus

Gauge Point Jig

To insure that specimens were properly marked for positioning prior to loading and that gauge points were properly positioned, a "gauge point jig" was designed and constructed. A photograph of the gauge point jig set upon a specimen is shown in FIGURE 8. Orthographic projections of the gauge point jig are shown in FIGURE A1. The arms which are attached to the circular plate are guides for marking the loading points on the opposite end of a specimen.

Strain Gauges and Associated Equipment

Two Sanborn Linearsyn Variable Differential Transformers were used for the measurement of strain. These gauges each have a primary coil which is excited by an external alternating current (from the Transducer Amplifier Indicator), and two secondary coils connected in series opposing. When the soft iron core is centered between the two secondary coils, equal voltage is induced into each of the secondary coils, and there is no output signal. When the core is moved away from the center, more voltage is induced in one secondary coil. The output signal voltage is then proportional to the core displacement.

Some pertinent data concerning the gauges used is given below:

1. Model no. — 595DT025
2. Stroke — ±0.025 inches from the null position.

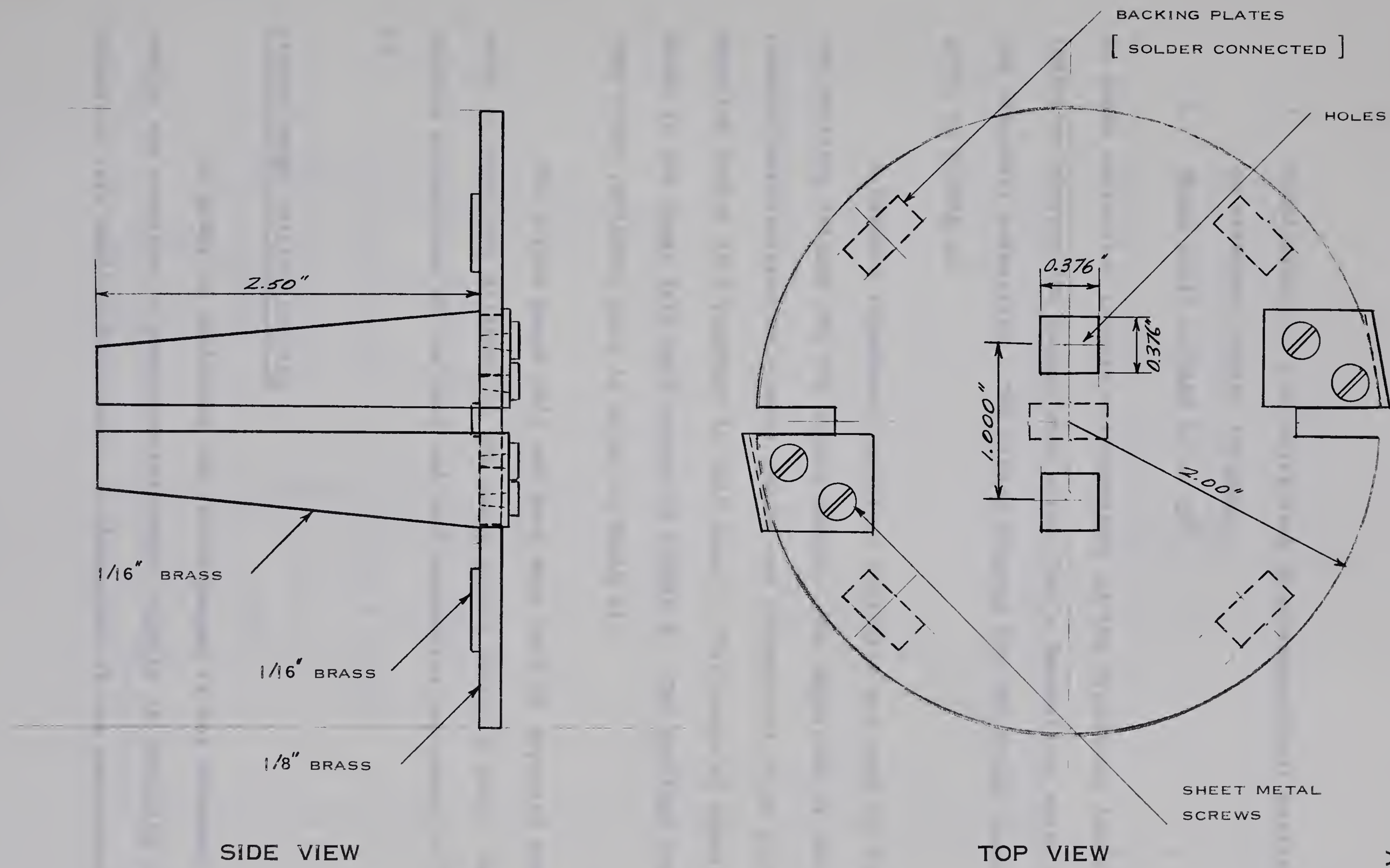

FIG. A1: GAUGE POINT JIG

3. Sensitivity — 3.40 volts/inch displacement/volt excitation at standard carrier frequency.
4. Phase shift at 2400 kc — 25°.

No phase correction circuit was necessary as the Transducer Amplifier Indicator whereto the gauges were wired, had a demodulator which made the necessary correction. The wiring diagram for the strain gauges is given in FIGURE A2.

A Sanborn Transducer Amplifier Indicator was used to supply the exciting voltage for the strain gauges. The magnitude of the signal received was displayed on a meter and/or was transferred to an external metering device (X-Y recorder in this case). This piece of apparatus is shown in the upper left hand corner of FIGURE 6. The settings used and some other pertinent data is given in TABLE A1.

The strain gauge coil and core were held by separate assemblies, which in turn were attached to the gauge points during a test. Orthographic projections of the coil and core assemblies are shown in FIGURE A3.

Strain Gauge Calibration Jig

In order to calibrate the strain gauges it was necessary to design and construct a precision instrument capable of producing and measuring very small deformations. A photograph of the constructed

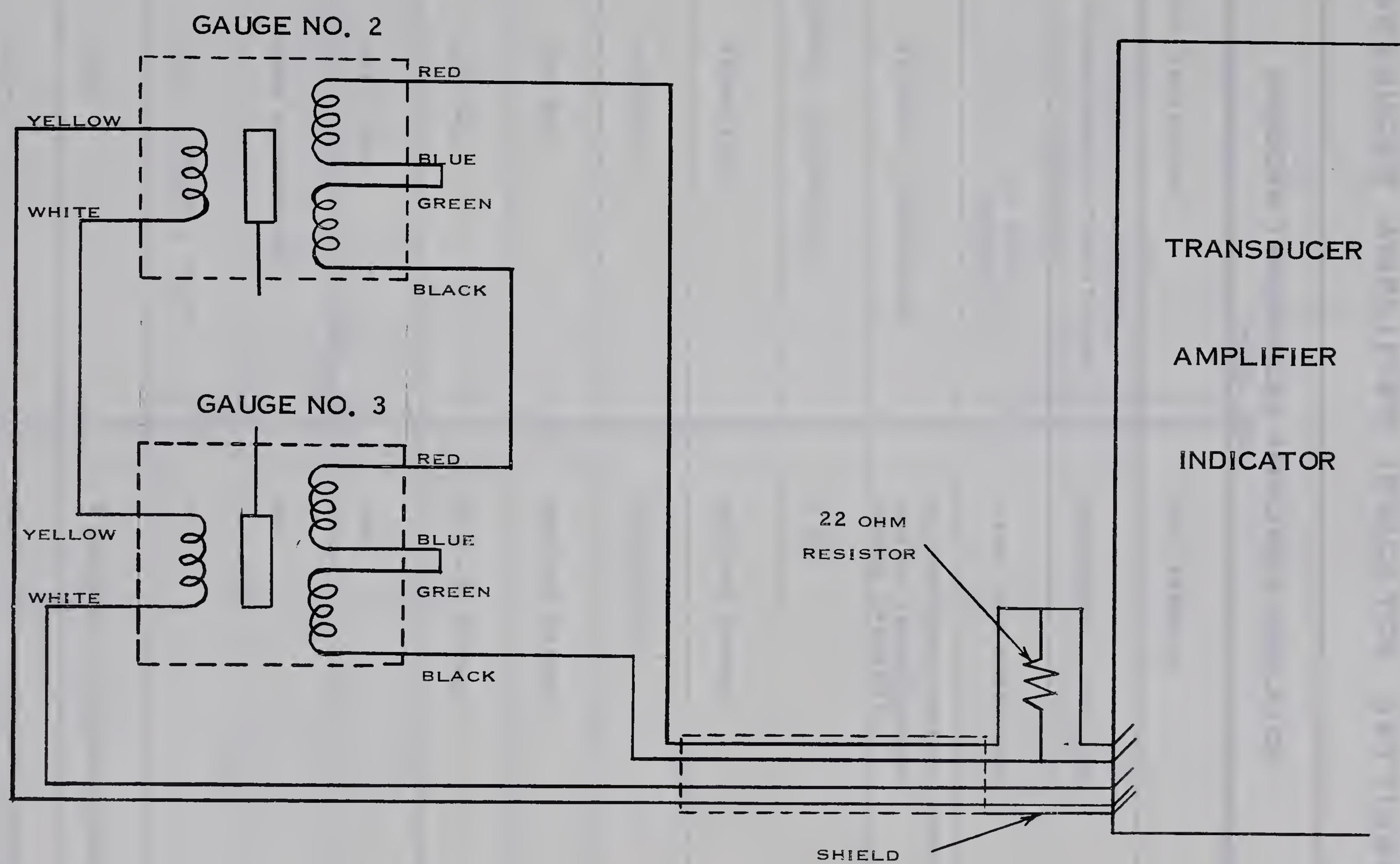

FIG. A2: WIRING DIAGRAM FOR STRAIN GAUGES

TABLE AI

TRANSDUCER AMPLIFIER INDICATOR SETTINGS

SANBORN TRANSDUCER AMPLIFIER INDICATOR MODEL 311A	
DATA: EXCITATION	5v, 2400cps
TRANSDUCER IMPEDENCE REQUIREMENTS AT EXCITATION TERMINALS	GREATER THAN 100 OHMS
AT INPUT TERMINALS	LESS THAN 5000 OHMS
EXTERNAL TRANSDUCER	2 LINEARSYN VARIABLE DIFFERENTIAL TRANSFORMERS MODEL 595DT025
SETTINGS: ATTENUATOR	x 50
SENSITIVITY	SET AND MARKED
POSITION	ADJUSTABLE
RES BAL.	SET AND MARKED
CAP BAL.	SET AND MARKED
USE - BAL	USE
ZERO SUPRESSION	OUT
FULL - BRIDGE - HALF	FULL
INPUT	5 TERMINAL TO STRAIN GAUGES
OUTPUT	JACK TO X AXIS OF X-Y RECORDER

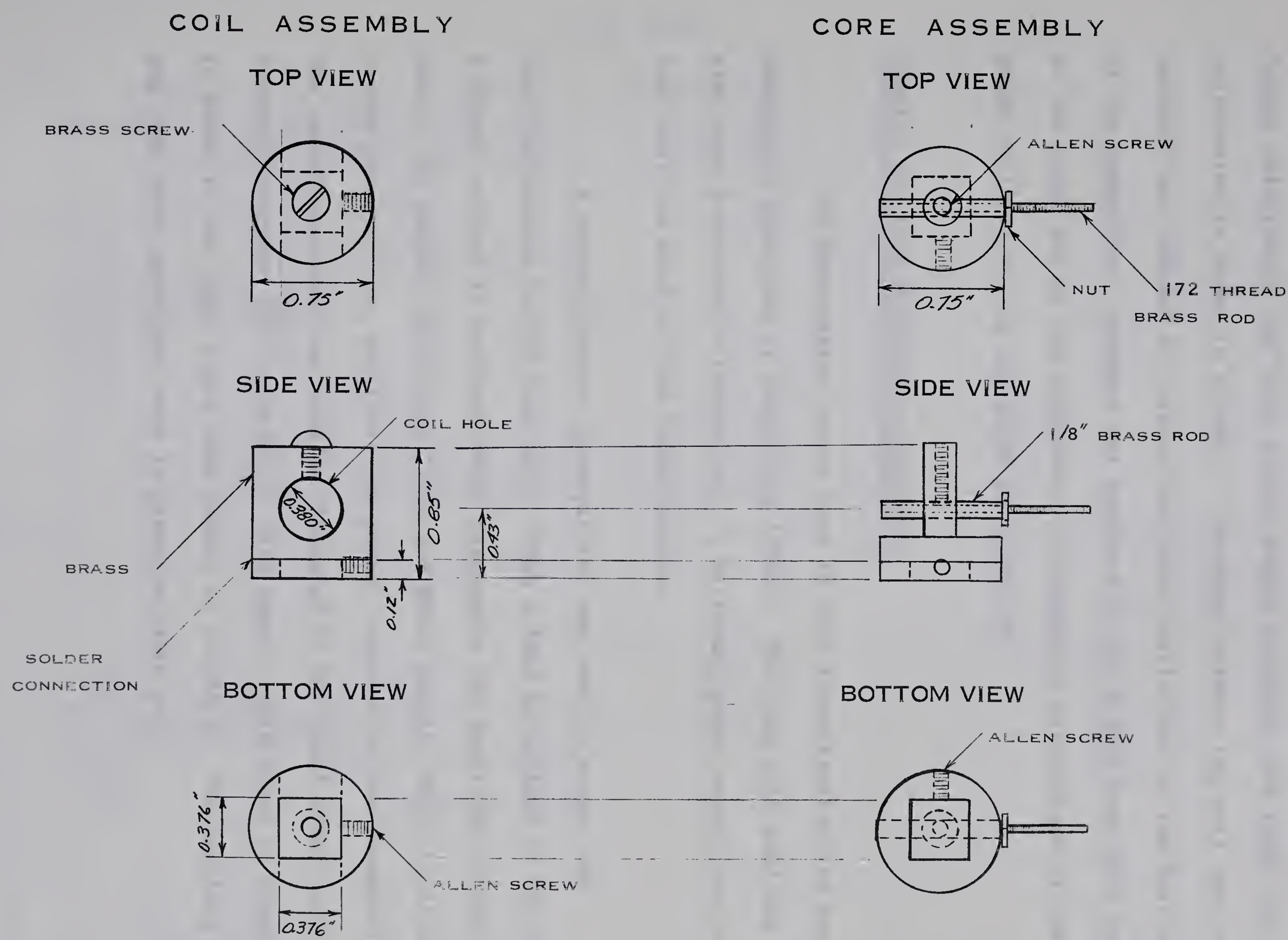

FIG. A3: STRAIN GAUGE CORE AND COIL ASSEMBLIES

"gauge calibration jig" with strain gauges attached, and ready for calibration is shown in FIGURE 7. Movement between the coil and core assembly was induced by turning the round knurled nut at the left end of the apparatus. Movement was measured by the 0.0001/inch dial gauge at the right end of the apparatus. Orthographic projections of the gauge calibration jig are given in FIGURE A4.

Loading and Load Measurement Apparatus

The compression tester used in this investigation has been adequately described by Christison (1966). The load cell used has also been described by Christison. A different power supply for the load cell was used in this investigation.

A Sanborn Carrier Preamplifier was used to supply the exciting voltage to the load cell. When a load is applied to the cell, a signal voltage is produced which represents the magnitude of that load. The Sanborn Driver Amplifier and Power Supply, which is attached to the preamplifier, amplifies the signal received by the preamplifier. The amplified signal can then be displayed on the panel meter and/or an external recorder (X-Y recorder in this case). This piece of apparatus is shown in the upper right hand corner of FIGURE 6. The settings used and some other pertinent data is given in TABLE A2.

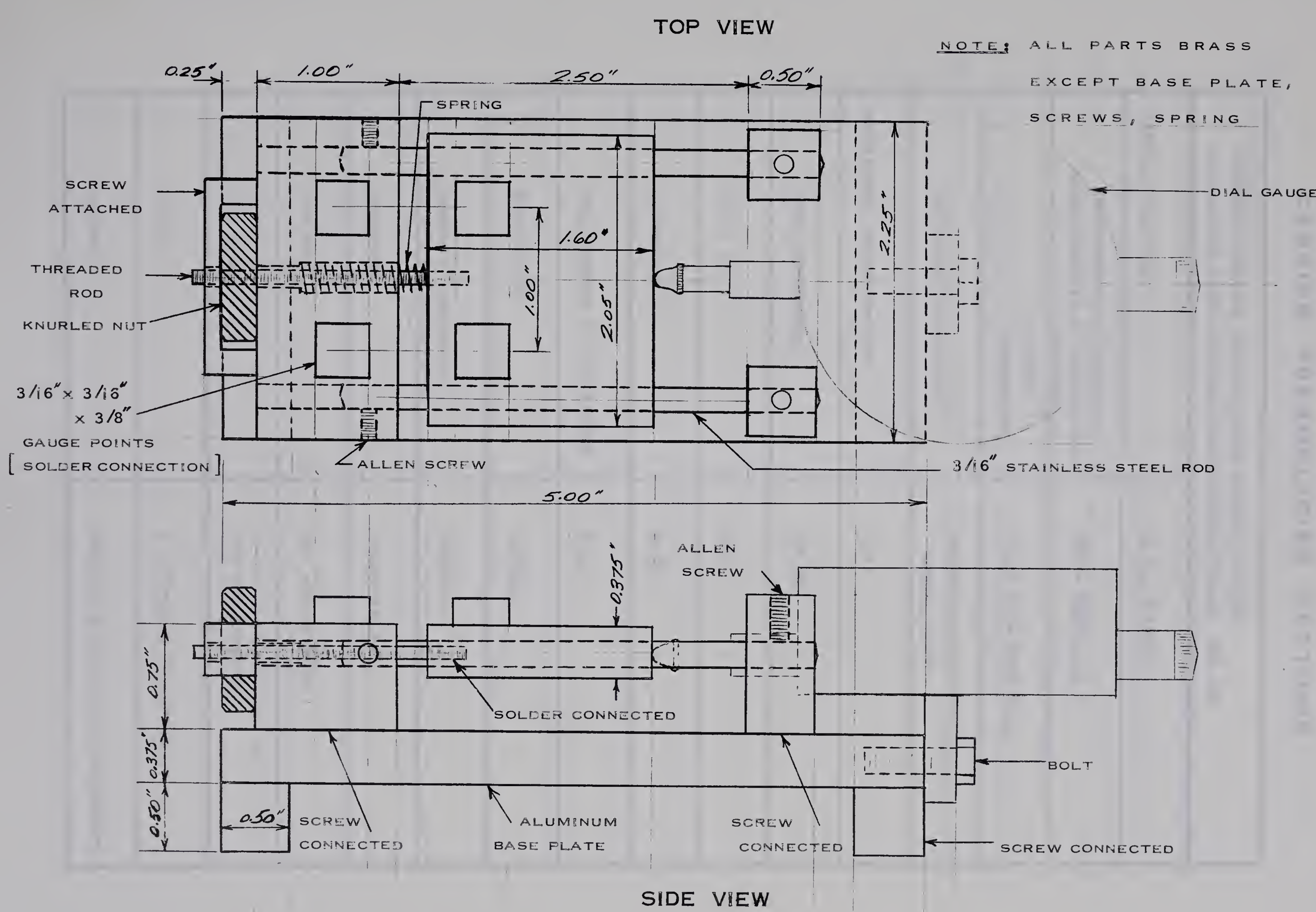

FIG. A4: GAUGE CALIBRATION JIG

TABLE A2
CARRIER PREAMPLIFIER SETTINGS

SANBORN CARRIER PREAMPLIFIER MODEL 150-1100 AND DRIVER AMPLIFIER AND POWER SUPPLY MODEL 150-300	
DATA: EXCITATION	4.5V, 2400CPS
TRANSDUCER IMPEDENCE REQUIREMENTS AT EXCITATION TERMINALS	100 - 300 OHMS
AT INPUT TERMINALS	LESS THAN 1000 OHMS
EXTERNAL TRANSDUCER	KWOYA MUSEN LOAD CELL MODEL LC-5
SETTINGS: GAUGE FACTOR	1.41
ZERO SUPRESSION	62.00
OUT - IN	OUT
ATTENUATOR	x 50
FULL BRIDGE - HALF BRIDGE	FULL
SENSITIVITY	LOCKED
OPERATE - BALANCE	OPERATE
POSITION	ADJUSTABLE
CAP BAL.	SET AND LOCKED
RES BAL.	SET AND LOCKED
INPUT	5 TERMINAL TO LOAD CELL
OUTPUT	JACK TO Y AXIS OF X-Y RECORDER

Recording Apparatus

A Hewlett Packard X-Y Recorder was used to automatically plot the load/strain test curves. The Y (load) axis was activated by the signal from the combined preamplifier and the driver amplifier and power supply. The X (strain) axis was activated by the signal from the transducer amplifier indicator. This piece of equipment is shown in the lower right hand corner of FIGURE 6. The settings used and some other pertinent data are given in TABLE A3.

TABLE A3

X-Y RECORDER SETTINGS AND INFORMATION

HEWLETT PACKARD X-Y RECORDER MODEL 7000A	
DATA: DC VOLTAGE RANGES [ON EACH AXIS]	17, FROM 0.1MV/INCH TO 20 V/INCH
AC VOLTAGE RANGES [ON EACH AXIS]	12, FROM 5MV/INCH TO 20V/INCH
TIME SWEEP RANGES [ON EACH AXIS]	8, FROM 0.5 TO 100 SEC/INCH
ZERO OFFSET	3 FULL SCALES ON X AXIS 4 FULL SCALES ON Y AXIS
SETTINGS	
PEN	IN, WHEN TESTING
SERVO	ON, WHEN TESTING
CHART POWER	ON HOLD WHEN TESTING
SWEEP	NOT USED
RECYCLE	OFF
X AXIS	
+ AND − TERMINALS	TO TRANSDUCER AMP. INDICATOR
GND, GUARD, ⊖ TERMINALS	INTERCONNECTED
AC-DC SWITCH	DC
RANGE	0.2V/INCH
ZERO OFFSET	ADJUSTABLE
Y AXIS	
+ AND − TERMINALS	TO CARRIER PREAMPLIFIER
GND, GUARD, ⊖ TERMINALS	INTERCONNECTED
AC-DC SWITCH	DC
RANGE	0.1V/INCH
ZERO OFFSET	ADJUSTABLE

APPENDIX B

CALIBRATIONS

- Dial Gauge on Gauge Calibration Jig

- Strain Gauges

- Load Cell

Dial Gauge on Gauge Calibration Jig

The calibration curve for the 0.001 inch dial gauge used is shown in FIGURE B1. Percentage errors in this calibration are so small as to be considered negligible. More error would likely be introduced by the "sticking" tendency inherent in this type of gauge.

Strain Gauges

A separate preliminary calibration of the three strain gauges available was conducted in order to select the two which were most closely matched. The selection was based upon the divergence curves obtained. To obtain these curves the positive or negative divergence of the X axis readings from the dial gauge readings was plotted. Then the two gauges whose divergence curves were most similar were selected. The divergence curves used for the gauge selection are not shown; however, they were similar in nature to the curves shown in FIGURES B3 and B4.

It was necessary to obtain an estimate of the errors involved in the measurement of strain, due to the difference in the sensitivity of the two gauges. The following procedure was used to determine the divergence curve for the combined gauges:

1. Both gauge no. 2 and 3 were placed upon the gauge calibration jig.

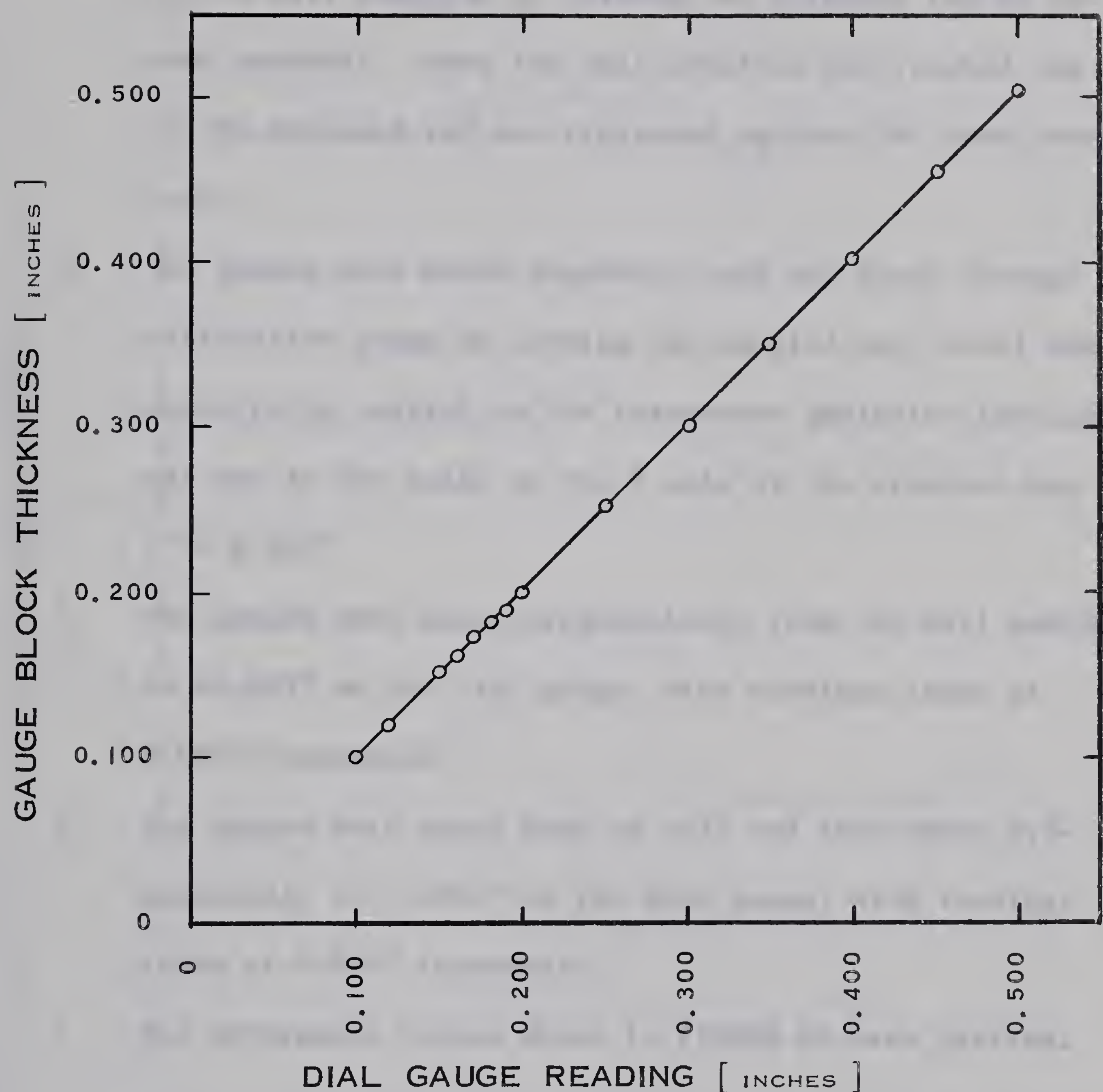

FIG. B1: DIAL GAUGE CALIBRATION CURVE

2. Gauge no. 2 output was shorted while gauge no. 3 was moved to the null position by turning the knurled nut.
3. Gauge no. 3 output was shorted while gauge no. 2 was moved to the null position by turning the threaded rod on the core assembly. When the null position was reached the nut on the threaded rod was tightened against the core assembly body.
4. The gauges were moved together, back and forth through the calibration range by turning the knurled nut, until the sensitivity control on the transducer amplifier indicator was set so the scale on the X axis of the recorder was 1" = 0.001".
5. The gauges were moved progressively from the null position to +0.025" on the dial gauge, with readings taken at 0.005" increments.
6. The gauges were moved back to null and then moved progressively to -0.025" on the dial gauge, with readings taken at 0.005" increments.
7. The divergence curves shown in FIGURE B2 were plotted.

Then it was necessary to determine the output of separate gauges throughout the same calibration range. The following procedure was used:

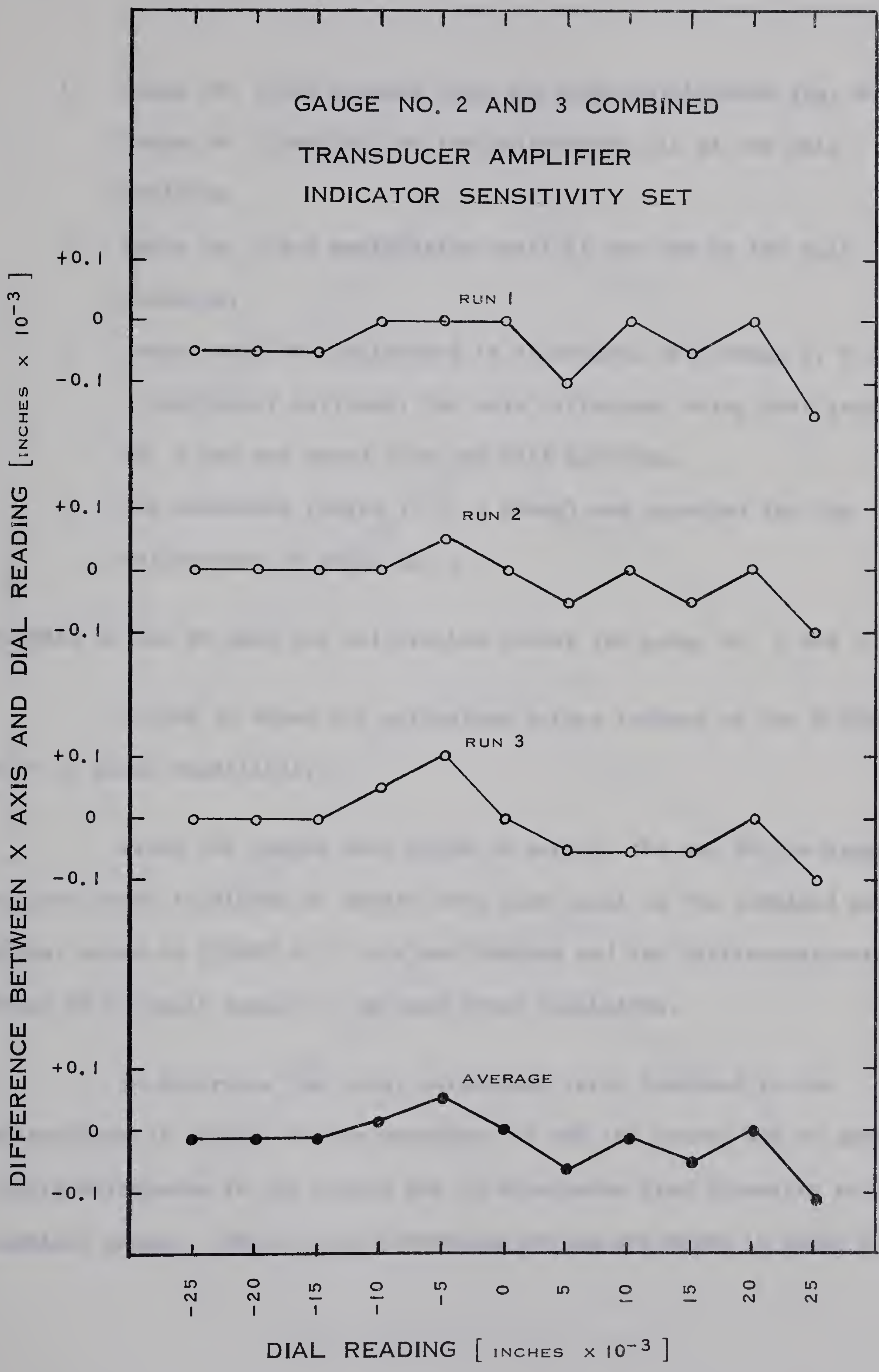

FIG. B2: COMBINED STRAIN GAUGE DIVERGENCE CURVES AT 70° F

1. Gauge no. 2 was removed from the gauge calibration jig, while gauge no. 3 was left on the calibration jig at the null position.
2. Gauge no. 2 was manipulated until it too was at the null position.
3. Gauge no. 3 was calibrated in accordance with steps 5, 6 and 7 previously outlined, the only difference being that gauge no. 2 was not moved from the null position.
4. The procedure (steps 1, 2, 3 above) was repeated for the calibration of gauge no. 2.

FIGURES B3 and B4 show the calibration curves for gauge no. 2 and 3.

FIGURE B5 shows the percentage errors induced by the difference in gauge sensitivity.

Since the gauges were wired in series, the sum of the gauge outputs shown in FIGURE B5 should have been equal to the combined gauge output shown in FIGURE B2. This was checked and the differences were found to be small enough to be considered negligible.

To determine the total percentage error involved in the measurement of strain, it was necessary to add the errors due to sensitivity difference to the errors due to divergence from linearity of the combined gauges. These total percentage errors are shown in TABLE B1.

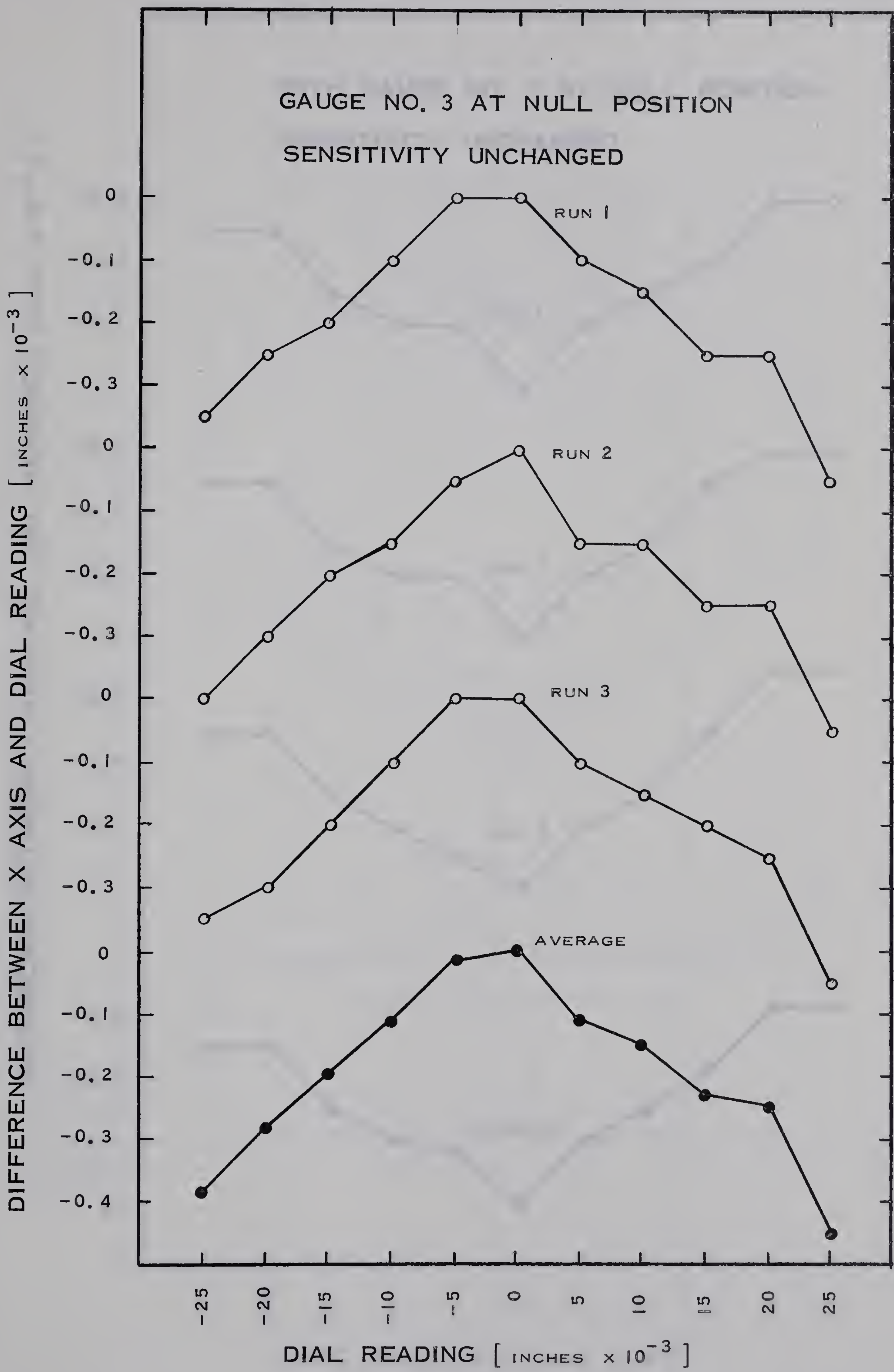

FIG. B3: DIVERGENCE CURVES FOR GAUGE NO. 2 AT 70° F

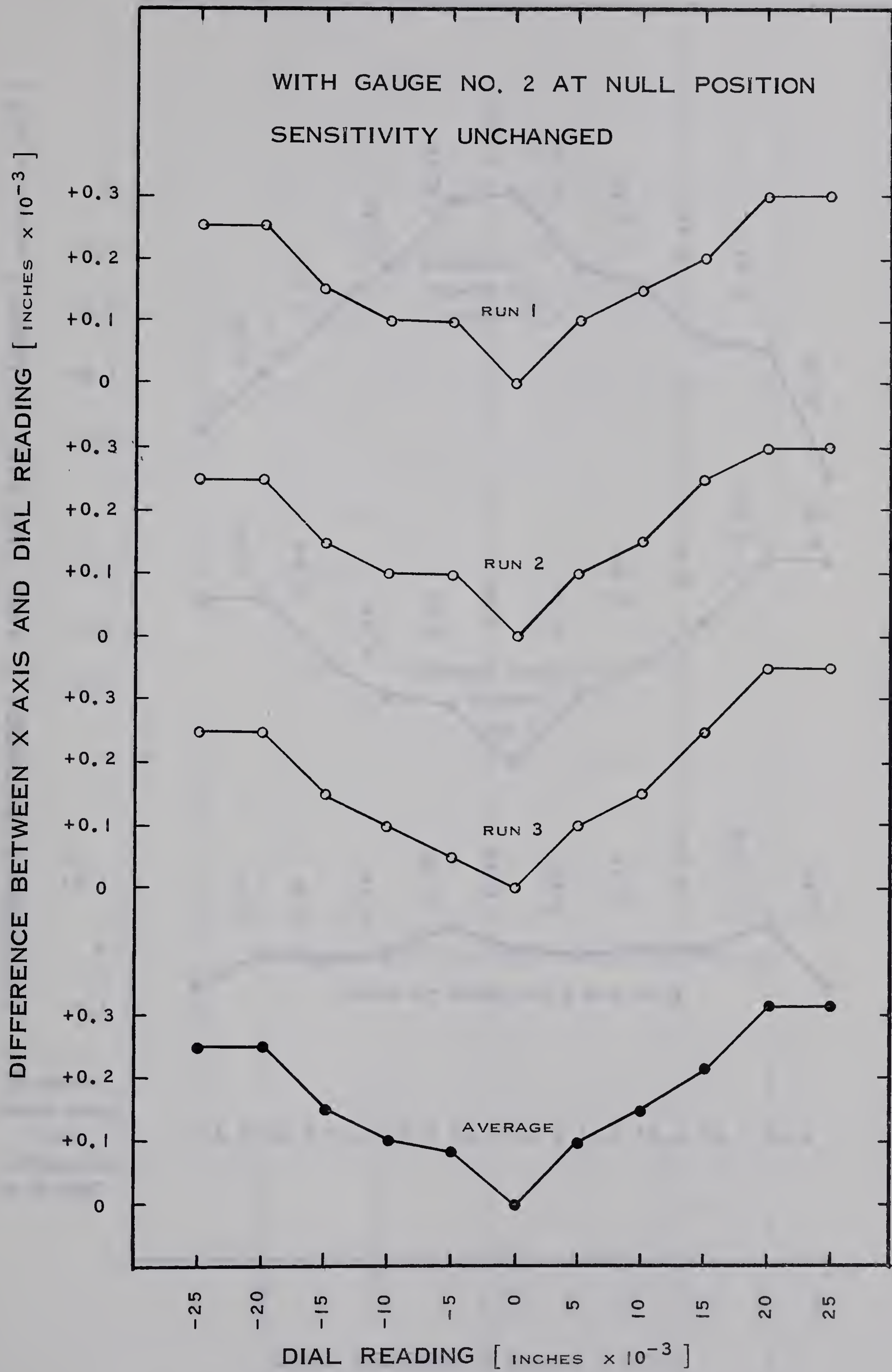

FIG. B4: DIVERGENCE CURVES FOR GAUGE NO. 3 AT 70° F

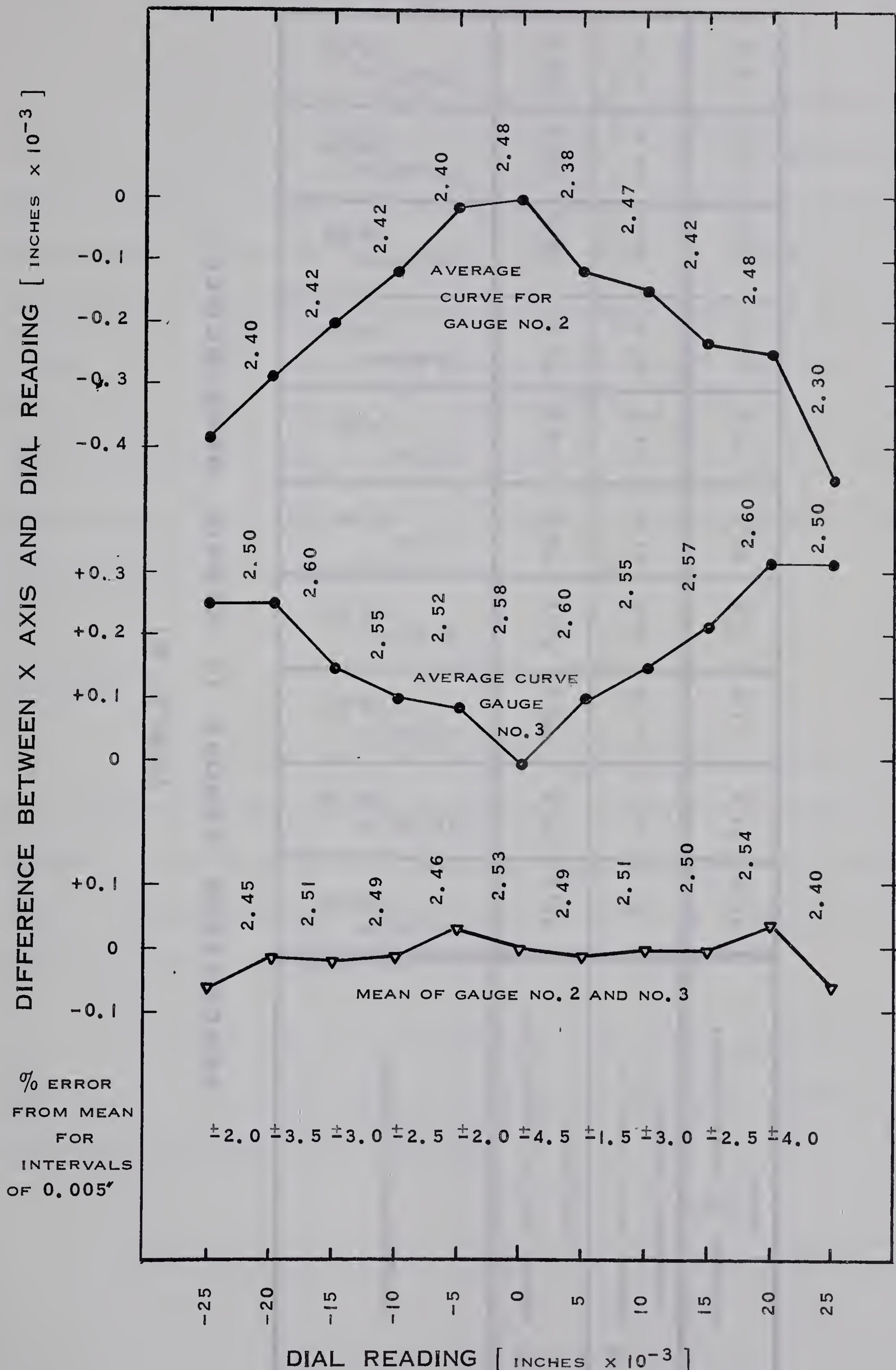

FIG. B5: PERCENTAGE ERRORS DUE TO GAUGE SENSITIVITY DIFFERENCE

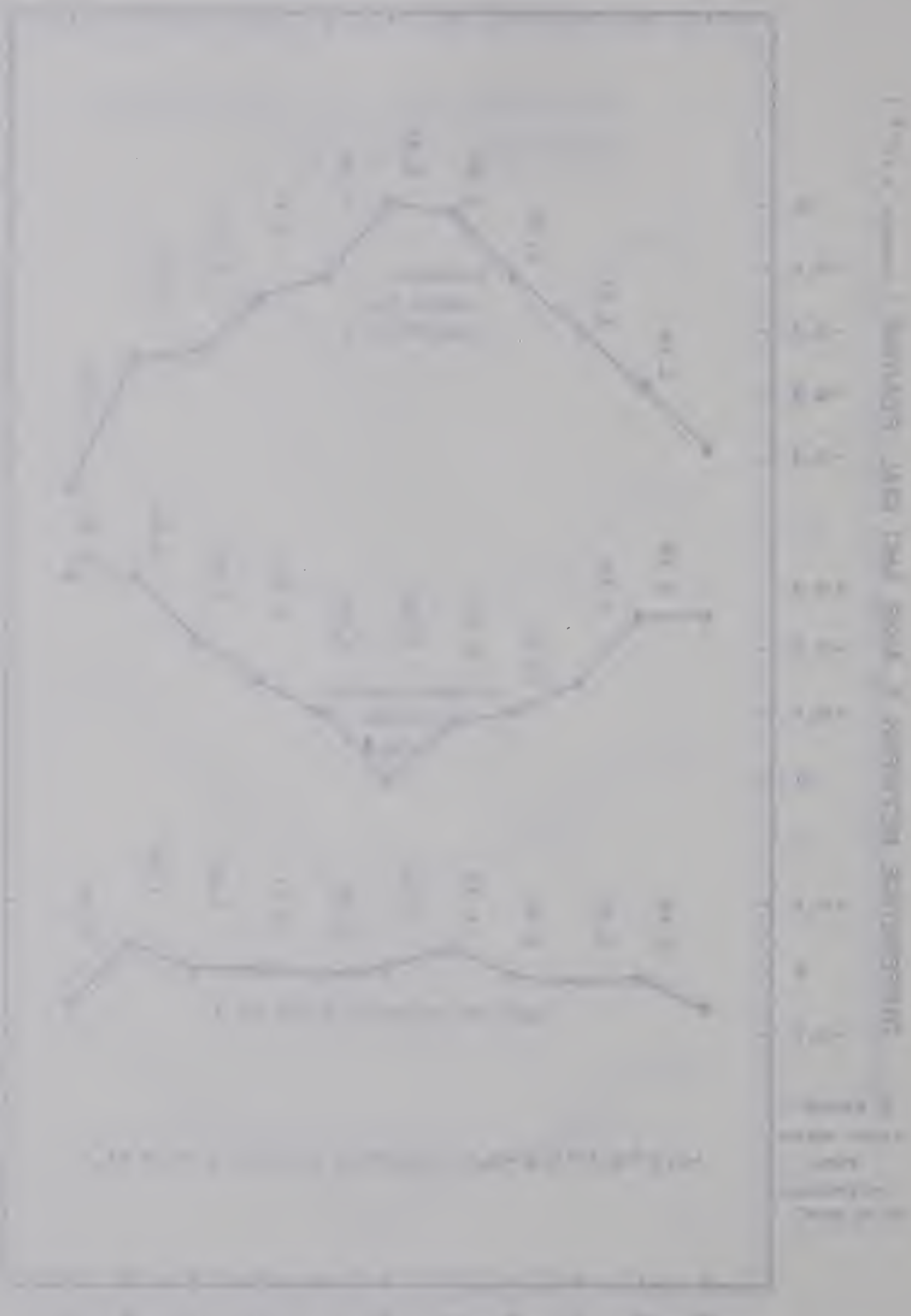

TABLE BI

PERCENTAGE ERRORS IN STRAIN MEASUREMENT

MEASUREMENT INTERVAL	-20.00 TO -25.00	-15.00 TO -20.00	-10.00 TO -15.00	-5.00 TO -10.00	0 TO -5.00	0 TO 5.00	5.00 TO 10.00	10.00 TO 15.00	15.00 TO 20.00	20.00 TO 25.00
% ERROR DUE TO SENSITIVITY DIFFERENCE	±2.0	±3.5	±3.0	±2.5	±2.0	±4.5	±1.5	±3.0	±2.5	±4.0
% ERROR FROM TRUE OF COMBINED GAUGES	0	0	-1.0	-0.5	+1.0	-1.5	+1.0	-0.5	+1.0	-2.5
MAXIMUM % MEASUREMENT ERROR	±2.0	±3.5	-4.0	-3.0	+3.0	-6.0	+2.5	-3.5	+3.5	-6.5

All the previous calibration work was done at room temperature, since only comparative values were of interest. Since the gauges were quite temperature sensitive it was mandatory that the final calibration be conducted at the test temperature ($0^{o}F$). The same procedure was used as that which was used to determine the divergence curve for the combined gauges. Divergence curves are shown in FIGURE B6. In this case the zero point on the curves was set at a gauge length of 1.00", so that it would not be necessary to change the core position after calibration. Calibration was only possible to -0.002" because of the limitation of the gauge calibration jig adjustment.

Load Cell

The load cell was calibrated in a Tinius Olsen Testing Machine Co. compression tester at room temperature. Calibration of the compression tester is periodically carried out by the company representatives. Maximum divergence from true was 1% which was considered sufficiently small to be neglected.

The load cell was a full bridge, temperature compensating device, so a room temperature calibration was acceptable. FIGURE B7 shows the calibration curve obtained.

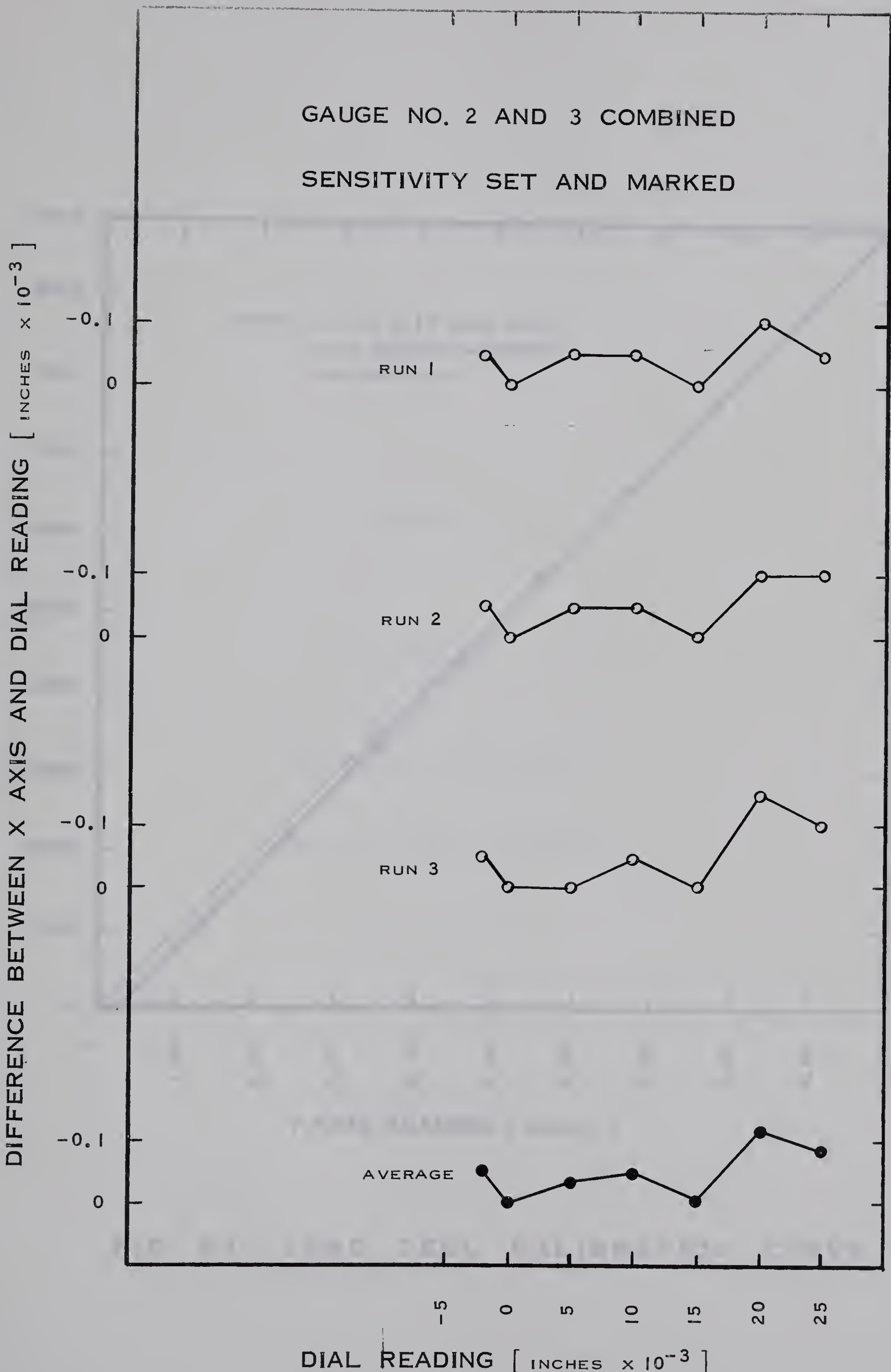

FIG. B6: COMBINED STRAIN GAUGE DIVERGENCE CURVES AT 0 F

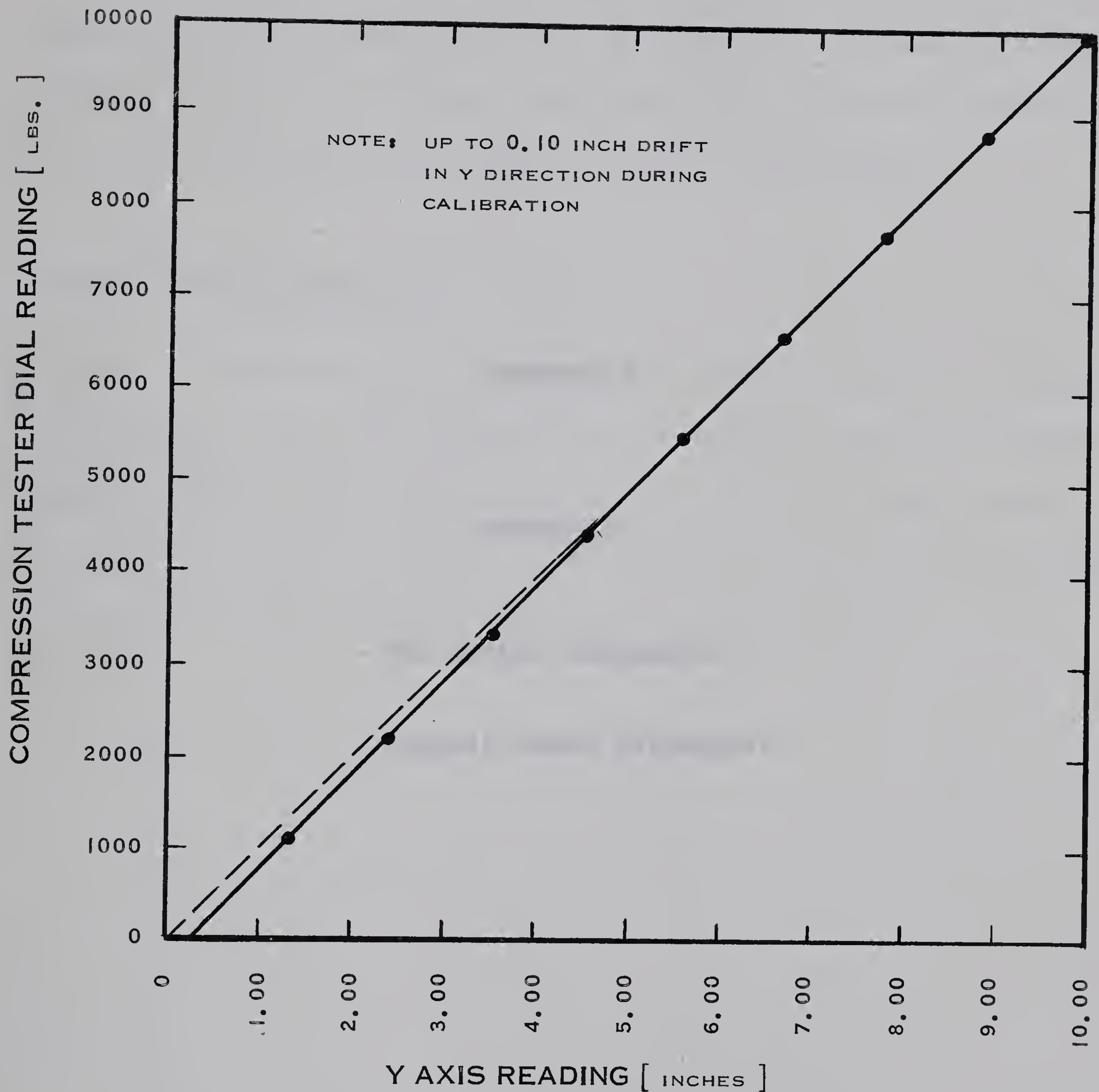

FIG. B7: LOAD CELL CALIBRATION CURVE

APPENDIX C

MATERIALS

- Mix Design Information

- Asphalt Cement Properties

Mix Design Information

The Marshall Stability Test properties and the test specimen properties for the mixes tested are summarized in TABLE C1. Field bulk asphalt contents were included where available. No other field data concerning the tests on the asphalt concrete was obtained.

Asphalt Cement Properties

Properties of the "as supplied" asphalt concrete are summarized in TABLE C2. The tests reported were conducted on samples of asphalt cement from the associated field projects. The same asphalt cements were used in the preparation of the test specimens. Properties of the asphalt cement used in the Marshall Stability Tests are not known.

TABLE C1

MARSHALL DESIGN AND TEST SPECIMEN DATA

[PREPARED FROM DATA SUPPLIED BY ALBERTA DEPT. OF HIGHWAYS]

AGGREGATE NO.	SPECIMEN ASPHALT SUPPLY NO.	SPECIFIED ASPHALT CEMENT PENETRATION	MARSHALL STABILITY TEST PROPERTIES																TEST SPECIMEN PROPERTIES							FIELD BULK % ASPHALT CONTENT
			COMPACTION BLOWS/FACE	STABILITY [LBS.]	FLOW [0.01 INS.]	% V. M. A.	% VOIDS FILLED	% AIR VOIDS TOTAL MIX	ASPHALT ADSORPTION %	SPECIFIC GRAV. OF ASPHALT	DENSITY [LBS./CU. FT.]	GRADATION [PERCENT PASSING]						SUGGESTED % ASPH. CONT.	GRADATION [PERCENT PASSING]						AVERAGE % ASPHALT CONT.	
												3/4	5/8	NO. 4	NO. 10	NO. 40	NO. 200		3/4	5/8	NO. 4	NO. 10	NO. 40	NO. 200		
0	3	200/300	* 65	1760	11.4	14.2	71.0	4.1	0.87	1.015	148.9	–	100	46	32	22	12	5.4	–	100	46	32	22	12.2	5.4	5.2
1	3			1185	8.8	15.0	72.0	4.2	0.56	1.019	146.6	–	100	51	37	16	6.5	5.5	–	100	51	37	15	3.8	5.6	5.2
2	1			1790	9.8	16.1	69.0	5.0	0.99	1.015	142.9	100	–	55	42	19	8.3	6.2	100	–	54	42	19	8.8	6.3	–
3	1			1770	9.8	16.9	72.5	4.7	1.03	1.019	141.8	100	–	56	45	23	12	5.9	100	–	55	45	23	11.2	6.0	–
4	6			1490	8.6	15.5	73.5	4.1	0.40	1.015	147.0	100	–	60	49	30	11	5.6	100	–	58	48	29	11.7	5.7	5.7
5	2			1770	11.8	16.6	70.0	4.6	1.18	1.019	144.3	100	–	60	47	26	13.3	6.7	100	–	59	47	25	12.6	6.8	5.6
6	2			1780	9.6	14.6	74.0	3.9	0.69	1.015	146.1	100	–	54	39	19	8.4	5.6	100	–	53	38	19	8.5	5.6	5.6
7	6			1460	10.4	13.5	74.0	3.5	0.50	1.015	148.5	100	–	47	33	19	8.9	5.0	100	–	45	32	18	8.0	5.0	–
8	2			1280	7.6	17.0	69.5	5.2	0.66	1.015	143.7	100	–	46	33	17	6.0	6.2	100	–	45	32	17	5.9	6.3	–
8	6			1280	7.6	17.0	69.5	5.2	0.66	1.015	143.7	100	–	46	33	17	6.0	6.2	100	–	45	32	17	5.9	6.3	–
9	1			1330	8.3	14.1	72.5	3.9	0.81	0.985	144.5	100	–	50	34	14	6.3	5.4	100	–	49	34	14	6.1	5.4	5.3
9	2			1555	8.7	14.1	70.5	4.2	0.80	1.015	144.6	100	–	51	34	15	6.8	5.4	100	–	48	34	14	6.6	5.5	5.3
9	3			1645	10.4	13.9	70.0	4.1	0.75	1.005	145.3	100	–	51	35	14	6.7	5.5	100	–	50	35	14	6.6	5.5	4.6

* USING NON STANDARD HAMMER. EQUIVALENT TO 75 BLOWS/FACE WITH STANDARD HAMMER

TABLE C2

AS SUPPLIED PROPERTIES OF ASPHALT CEMENTS

[PREPARED FROM DATA SUPPLIED BY ALBERTA RESEARCH COUNCIL]

AGGREGATE NO.	ASPHALT CEMENT SUPPLY NO.	PENETRATION			SOFTENING POINT	VISCOSITY			
		AT 77°F	AT 39.2°F	AT 32.0°F	°F	AT 140°F [POISE]	SHEAR RATE SEC −1	AT 77°F AT 1000 ERGS/SEC/CC [POISE]	SLOPE 'C'
0	3	280	69	41	107	492	18.9	1.69	.890
1	3	280	69	41	107	492	18.9	1.69	.890
2	1	245	52	26	110	230	28.6	0.92	.980
3	1	245	52	26	110	230	28.6	0.92	.980
4	6	316	68	45	104	304	29.7	1.59	.925
5	2	220	43	27	99	591	18.0	1.94	.993
6	2	220	43	27	99	591	18.0	1.94	.993
7	6	417	95	55	102	197	33.5	0.70	.914
8	6	417	95	55	102	197	33.5	0.70	.914
8	2	–	–	–	–	–	–	–	–
9	1	265	68	40	103	237	28.9	2.86	.811
9	2	215	62	38	101	610	16.2	3.25	.904
9	3	217	58	35	102	544	18.6	2.59	1.079

APPENDIX D

COMPUTER PROGRAMS

- Inventory

- Analysis of Test Results

Inventory

The inventory program and the output for the highway sections studied is presented in FIGURE D1. Inventory output for the northbound lanes of highway 2-D-2/1 was printed after each stage of input, for illustration purposes only. The diagonal stepped line on page D7 of FIGURE D1 indicates the extent of progression of the inventory information with each stage of input data. The large numbers at the right hand edge of the page represent the stage of input and output.

The initial stage of input consisted of seven data cards which contained all the information shown in the stage 2 output except the trailing zeros in the contract boundary column. Stage 1 was not output due to a lack of space on the page.

Stage 2 input consisted of one data card which contained 9 N 2-D-2/1 2002430-2481000 and the 0 in the "contract boundary" column. This indicated that there were no subgrade contract boundaries between these chainages. Consequently the inventory sections which were formed by the stage 1 input remained unchanged. The leading 9 signified to the program that this was the last data card for the input stage.

Stage 3 input consisted of two data cards, the first of which contained 0 N 2-D-2/1 2002430-2173000, CI in the "embankment soil" column and 64 in the "year finished" column. The second card contained 9 N 2-D-2/1 2173001-2481000, CL in the "embankment soil" column and 64 in

```
  INT INVENTORY PROG                              FORTRAN SOURCE LIST
ISN        SOURCE STATEMENT

  0 $IBFTC INV      NODECK
    C
    C
    C         THIS PROGRAM UPDATES AN INVENTORY OF BASIC HIGHWAY PROPERTIES
    C         CONSIDERED TO BE RELEVANT TO THERMAL CRACKING OF ASPHALT
    C         CONCRETE.  THERE ARE 7 STAGES OF INPUT DATA.  EACH RESULTANT
    C         INVENTORY SECTION IS UNIQUE WITH RESPECT TO THE INPUT VARIABLES.
    C
    C
  1          LLCC=0
  2     171 CONTINUE
  3          DIMENSION IFROM(80),ITO(80),IQN(80),INS(80),IBS(80),       IES(80),
            1IYRS(80),IBB(80),IT(80,5),IC(80,5),IYRB(80),ITC(80,3),IPIT(80),
            2IPEN(80),ISUP(80),KMAX(80),KKKA(10),KKKKA(10)
  4          WRITE(6,1010)
  5    1010 FORMAT(1H1,86H   IDENTIFICATION INFORMATION        SUB-         BASE C
            1OURSE INFORMATION        SURF COURSE/35X,47HGRADE
            2                         INFO/36X,4HINFO/45X,42HBOTTOM      -LAYER-      TO
            3P        BOT         TOP/1X,80HT                                C      C      Y
            4 C    T      T      T      T      T        Y     T T T/1X,86HR       S      .      .
            5         H   N   O   E   R   U   HD      HD      HD      HD     HD      R    H H H    A A
            6)
  6          WRITE(6,1011)
  7    1011 FORMAT(1X,
            6    86HA        S U         S          S       A    A    N    M        N   IE     IE    IE
            7IE      IE              I  I  I  A  S  S/1X,86HV    H  E  B           T            T      I    T
            7T    B    F    T    CS  B  CS  B  CS  B  CS  B  CS  B    F      C  C  C  G  P  P/4X,83HW  C
            8        A       T        A          N            R           I    R    KICI  KICI  KICI  KICI  KICI    I
            9K  K  K  G  H  H)
 10          WRITE(6,1012)
 11    1012 FORMAT(       1X,80HD    Y  T  S            T      O      T              S          S    N          NGL
            IN NGLN NGLN NGLN NGLN    N       N N N/1X,86HI          I  E              I              I
            2E    O    B    O    I    B    E  AD  E  AD  E  AD  E  AD  E  AD    I      E  E  E  P  P  S/1X,86H
            3R    N  O  C              O               O          Q    I     D    I     S     D    SNSE SNSE SNSE SNSE S
            4NSE    S       S  S  S  I  E  U/1X,86HN    O  N  T              N                N          N    L    Y    L
            5H    Y    SOSR SOSR SOSR SOSR SOSR    H       S  S  S  T  N  P)
 12          INTEGER TEST
 13          DO151K=1,80
 14          IES(K)=0
 15          IYRS(K)=0
 16     151 CONTINUE
 20          DO152K=1,80
 21          IYRB(K)=0
 22          IBB(K)=0
 23     152 CONTINUE
 25          DO153K=1,80
 26          DO154N=1,5
 27          IT(K,N)=0
 30          IC(K,N)=0
 31     154 CONTINUE
 33     153 CONTINUE
 35          DO155K=1,80
 36          DO156M=1,3
 37          ITC(K,M)=0
 40     156 CONTINUE
```

FIG. DI: INVENTORY PROGRAM AND OUTPUT

[PAGE D2 TO D9 INCL.]

```
 INT  INVENTORY PROG                              FORTRAN SOURCE LIST INV
ISN           SOURCE STATEMENT

  42     155 CONTINUE
  44         DO157K=1,80
  45         IPIT(K)=0
  46         IPEN(K)=0
  47         ISUP(K)=0
  50     157 CONTINUE
  52         LLCC=LLCC+1
  53         LL=1
  54         KMAX(LL)=0
  55         K=0
  56     102 K=K+1
  57         READ(5,1001) TEST,IFROM(K),ID,ITO(K),ILANE,INO,ISECT,ISUBT,     ISL,
            1ISUBB,IQN(K),INS(K)
  70    1001 FORMAT(1X,I11,I17,A1,I17,A2,I12,A3,I11,A1,I11,I12,A3,I12,A3,    I13,
            1I12,1X,5(I13,A2),I13,3I2,2A1,I11)
  71         IF(TEST.EQ.8) GO TO 172
  74         IF(TEST.EQ.9) GO TO 101
  77         GO TO 102
 100     101 CONTINUE
 101     111 LL=LL+1
 102         IF(LL.EQ.8) GO TO 150
 105         KMAX(LL)=K
 106         J=KMAX(LL-1)
 107     170 J=J+1
 110         IF(J.GT.KMAX(LL-1)+1) GO TO 104
 113         K=KMAX(LL)
 114     104 K=K+1
 115         GO TO (12345,112,113,114,115,116,117),LL
 116     112 READ(5,1002) TEST,IFROM(K),ID,ITO(K),ILANE,INO,ISECT,ISUBT,     ISL,
            1ISUBB,IBS(K)
 127         GO TO 122
 130     113 READ(5,1003) TEST,IFROM(K),ID,ITO(K),ILANE,INO,ISECT,ISUBT,     ISL,
            1ISUBB,IES(K),IYRS(K)
 141         GO TO 122
 142     114 READ(5,1004) TEST,IFROM(K),ID,ITO(K),ILANE,INO,ISECT,ISUBT,     ISL,
            1ISUBB,IBB(K)
 153         GO TO 122
 154     115 READ(5,1005) TEST,IFROM(K),ID,ITO(K),ILANE,INO,ISECT,ISUBT,     ISL,
            1ISUBB,IT(K,1),IC(K,1),IT(K,2),IC(K,2),IT(K,3),IC(K,3),      IT(K,4),
            2IC(K,4),IT(K,5),IC(K,5),IYRB(K)
 165         GO TO 122
 166     116 READ(5,1006) TEST,IFROM(K),ID,ITO(K),ILANE,INO,ISECT,ISUBT,     ISL,
            1ISUBB,ITC(K,1),ITC(K,2),ITC(K,3)
 177         GO TO 122
 200     117 READ(5,1007) TEST,IFROM(K),ID,ITO(K),ILANE,INO,ISECT,ISUBT,     ISL,
            1ISUBB,IPIT(K),IPEN(K),ISUP(K)
 211         GO TO 122
 212    1020 FORMAT(1X,A2,I12,A3,I11,A1,I11,1X,I17,1X,I17,I12,A3,2X,I11,A3,
            1I13,2X,I11,1X,5(I13,A2),I13,2X,3I2,1X,A1,1X,A1,I12)
 213    1002 FORMAT(1X,I11,I17,A1,I17,A2,I12,A3,I11,A1,I11,5X,I12)
 214    1003 FORMAT(1X,I11,I17,A1,I17,A2,I12,A3,I11,A1,I11,7X,A3,I13)
 215    1004 FORMAT(1X,I11,I17,A1,I17,A2,I12,A3,I11,A1,I11,13X,I12)
 216    1005 FORMAT(1X,I11,I17,A1,I17,A2,I12,A3,I11,A1,I11,16X,5(I13,A2),I13)
 217    1006 FORMAT(1X,I11,I17,A1,I17,A2,I12,A3,I11,A1,I11,44X,3I2)
 220    1007 FORMAT(1X,I11,I17,A1,I17,A2,I12,A3,I11,A1,I11,50X,2A1,I11)
```

```
      INT  INVENTORY PROG                           FORTRAN SOURCE LIST INV
  ISN          SOURCE STATEMENT

  221    122 IF(IFROM(K).GE.IFROM(J)) GO TO 105
  224        IFROM(K)=IFROM(J)
  225    105 IF(ITO(K).LE.ITO(J)) GO TO 106
  230        KK=ITO(K)
  231    110 ITO(K)=ITO(J)
  232        GO TO 107
  233    106 KK=0
  234    107 CONTINUE
  235        GO TO (12345,132,133,134,135,136,137),LL
  236    137 DO139M=1,3
  237        ITC(K,M)=ITC(J,M)
  240    139 CONTINUE
  242    136 IYRB(K)=IYRB(J)
  243        DO138N=1,5
  244        IC(K,N)=IC(J,N)
  245        IT(K,N)=IT(J,N)
  246    138 CONTINUE
  250    135 IBB(K)=IBB(J)
  251    134 IYRS(K)=IYRS(J)
  252        IES(K)=IES(J)
  253    133 IBS(K)=IBS(J)
  254    132 INS(K)=INS(J)
  255        IQN(K)=IQN(J)
  256        KMAXK=KMAX(LL)
  257        IF(LLCC.EQ.1) GO TO 173
  262        IF(LL.LT.7) GO TO 174
  265    173 WRITE(6,1020)ILANE,INO,ISECT,ISUBT,ISL,ISUBB,IFROM(K),ITO(K),
            1IQN(K),INS(K),IBS(K),IES(K),IYRS(K),IBB(K),IT(K,1),IC(K,1),
            2IT(K,2),IC(K,2),IT(K,3),IC(K,3),IT(K,4),IC(K,4),IT(K,5),  IC(K,5),
            3IYRB(K),(ITC(K,M),M=1,3),IPIT(K),IPEN(K),ISUP(K)
  272    174 IF(ITO(K).EQ.ITO(KMAXK)) GO TO 109
  275        IF(KK.GT.ITO(J)) GO TO 108
  300        IF(ITO(K).EQ.ITO(J)) GO TO 170
  303        GO TO 104
  304    108 GO TO (12345,142,143,144,145,146,147),LL
  305    142 KKK=IBS(K)
  306        K=K+1
  307        IBS(K)=KKK
  310        GO TO 125
  311    143 KKK=IES(K)
  312        KKKK=IYRS(K)
  313        K=K+1
  314        IES(K)=KKK
  315        IYRS(K)=KKKK
  316        GO TO 125
  317    144 KKK=IBB(K)
  320        K=K+1
  321        IBB(K)=KKK
  322        GO TO 125
  323    145 DO158N=1,5
  324        KKKA(N)=IT(K,N)
  325        KKKKA(N)=IC(K,N)
  326    158 CONTINUE
  330        KKKKK=IYRB(K)
  331        K=K+1
```

```
  INT  INVENTORY PROG                          FORTRAN SOURCE LIST INV
 ISN          SOURCE STATEMENT

 332          DO159N=1,5
 333          IT(K,N)=KKKA(N)
 334          IC(K,N)=KKKKA(N)
 335     159  CONTINUE
 337          IYRB(K)=KKKKK
 340          GO TO 125
 341     146  DO148M=1,3
 342          KKKA(M)=ITC(K,M)
 343     148  CONTINUE
 345          K=K+1
 346          DO149M=1,3
 347          ITC(K,M)=KKKA(M)
 350     149  CONTINUE
 352          GO TO 125
 353     147  KKK=IPEN(K)
 354          KKKK=ISUP(K)
 355          KKKKK=IPIT(K)
 356          K=K+1
 357          IPEN(K)=KKK
 360          ISUP(K)=KKKK
 361          IPIT(K)=KKKKK
 362          GO TO 125
 363     125  IFROM(K)=ITO(J)+1
 364          ITO(K)=KK
 365          J=J+1
 366          IF(ITO(K).GT.ITO(J)) GO TO 110
 371          GO TO (12345,162,163,164,165,166,167),LL
 372     167  DO169M=1,3
 373          ITC(K,M)=ITC(J,M)
 374     169  CONTINUE
 376     166  IYRB(K)=IYRB(J)
 377          DO168N=1,5
 400          IC(K,N)=IC(J,N)
 401          IT(K,N)=IT(J,N)
 402     168  CONTINUE
 404     165  IBB(K)=IBB(J)
 405     164  IYRS(K)=IYRS(J)
 406          IES(K)=IES(J)
 407     163  IBS(K)=IBS(J)
 410     162  INS(K)=INS(J)
 411          IQN(K)=IQN(J)
 412          IF(LLCC.EQ.1) GO TO 175
 415          IF(LL.LT.7) GO TO 176
 420     175  WRITE(6,1020)ILANE,INO,ISECT,ISUBT,ISL,ISUBB,IFROM(K),ITO(K),
             1IQN(K),INS(K),IBS(K),IES(K),IYRS(K),IBB(K),IT(K,1),IC(K,1),
             2IT(K,2),IC(K,2),IT(K,3),IC(K,3),IT(K,4),IC(K,4),IT(K,5), IC(K,5),
             3IYRB(K),(ITC(K,M),M=1,3),IPIT(K),IPEN(K),ISUP(K)
 425     176  IF(TEST.EQ.9) GO TO 111
 430          IF(ITO(K).EQ.ITO(J)) GO TO 170
 433          GO TO 104
 434     109  CONTINUE
 435          IF(TEST.EQ.9) GO TO 111
 440   12345  CONTINUE
 441          GO TO 170
 442     150  GO TO 171
```

```
  INT  INVENTORY PROG                            FORTRAN SOURCE LIST INV
ISN        SOURCE STATEMENT

443    172 CONTINUE
      C
      C
      C         EXPLANATION OF CODING-
      C
      C               DESIGNATION NO. - 9 = PIT RUN
      C
      C               CLASS - Z = DOUBLE SURFACE TREATMENT
      C
      C               BINDER - BLANK = WATERBOUND
      C                      - A = ASPHALT STABILIZED
      C                      - P = PLANT MIX
      C                      - * = 49-A-2 - FIRST 3 LAYERS CONSTR FINISH 60
      C                      - * = 49-A-3 - FIRST LAYER CONSTR FINISH 59
      C
      C               AGG PIT - 9 = PIT 210 (PONOKA NO.3)
      C                         8 = PRSP 359 (WATINO)
      C                         7 = PRSP 439 (WANHAM)
      C                         6 = PRSP 262 (ADAMS)
      C                         5 = PRSP 406 (DUFVA)
      C                         4 = PRSP 326
      C                         3 = PRSP 290 (WOITTE)
      C                         2 = PIT 790 (MILLER-GREKUL)
      C                         1 = PIT 208 (BEARSPAW)
      C                         0 = PIT 1451 (ELBOW RIVER)
      C                         X = SECTION NOT TO BE STUDIED
      C
      C               ASPH PEN - C = 200/300
      C
      C
444          STOP
445          END
```

IDENTIFICATION INFORMATION								SUB-GRADE INFO			BASE COURSE INFORMATION																						SURF COURSE INFO						
												BOTTOM								-LAYER-								TOP					BOT					TOP	
TRAV DIR	HWY NO	SECTION	SUB SECT	STATION	TO STATION	CHAIN EQN	NAT SOIL	CONTR BODY	EMB SOIL	YR FINISH	CONTR BODY	THICKNESS	DESIGN NO	CLASS	BINDER	THICKNESS	DESIGN NO	CLASS	BINDER	THICKNESS	DESIGN NO	CLASS	BINDER	THICKNESS	DESIGN NO	CLASS	BINDER	THICKNESS	DESIGN NO	CLASS	BINDER	YR FINISH	THICKNESS	THICKNESS	THICKNESS	AGG	ASPH PEN	ASPH SUP	1
N	2-	D-	2/1	2002430	2042000	0	CL	0	000	0	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2042001	2063000	0	CI	0	000	0	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2063001	2089000	0	CL	0	000	0	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2089001	2105000	0	CH	0	000	0	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2105001	2138000	0	CL	0	000	0	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	2
N	2-	D-	2/1	2138001	2173000	0	CI	0	000	0	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2173001	2481000	0	CL	0	000	0	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2002430	2042000	0	CL	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2042001	2063000	0	CI	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2063001	2089000	0	CL	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2089001	2105000	0	CH	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	3
N	2-	D-	2/1	2105001	2138000	0	CL	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2138001	2173000	0	CI	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2173001	2481000	0	CL	0	CL	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2002430	2042000	0	CL	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2042001	2063000	0	CI	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2063001	2089000	0	CL	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	4
N	2-	D-	2/1	2089001	2105000	0	CH	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2105001	2138000	0	CL	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2138001	2173000	0	CI	0	CI	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2173001	2481000	0	CL	0	CL	64	0		0	0	0		0	0	0		0	0	0		0	0	0		0	0	0	0	0	0	0	0	0	0	
N	2-	D-	2/1	2002430	2042000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2042001	2063000	0	CI	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2063001	2089000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2089001	2100500	0	CH	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2100501	2105000	0	CH	0	CI	64	0	15	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	5
N	2-	D-	2/1	2105001	2114500	0	CL	0	CI	64	0	15	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2114501	2138000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2138001	2173000	0	CI	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2173001	2481000	0	CL	0	CL	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	0	0	0	0	0	0	
N	2-	D-	2/1	2002430	2042000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2042001	2063000	0	CI	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2063001	2089000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2089001	2100500	0	CH	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2100501	2105000	0	CH	0	CI	64	0	15	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	6
N	2-	D-	2/1	2105001	2114500	0	CL	0	CI	64	0	15	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2114501	2138000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2138001	2173000	0	CI	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2173001	2481000	0	CL	0	CL	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	0	0	0	
N	2-	D-	2/1	2002430	2042000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2042001	2063000	0	CI	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2063001	2089000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2089001	2100500	0	CH	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2100501	2105000	0	CH	0	CI	64	0	15	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	7
N	2-	D-	2/1	2105001	2114500	0	CL	0	CI	64	0	15	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2114501	2138000	0	CL	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2138001	2173000	0	CI	0	CI	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2173001	2403887	0	CL	0	CL	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	1	
N	2-	D-	2/1	2403888	2481000	0	CL	0	CL	64	0	10	2	B		2	1	A		2	1	A	A	-	0			-	0			65	2	2	-0	9	C	2	

IDENTIFICATION INFORMATION					SUB-GRADE INFO					BASE COURSE INFORMATION						SURF COURSE INFO			
TRAV DIRN	HWY NO SECTION SUBSECT	STATION	TO STATION	CHAIN EQN	NAT SOIL	CONTR BDY	EMB SOIL	YR FINISH	CONTR BDY	BOTTOM THICKNESS DESIG NO CLASS BINDER	-LAYER- THICKNESS DESIG NO CLASS BINDER	THICKNESS DESIG NO CLASS BINDER	THICKNESS DESIG NO CLASS BINDER	TOP THICKNESS DESIG NO CLASS BINDER	YR FINISH	BOT ... TOP THICKNESS	AGG PIT	ASPH PEN	ASPH SUP
S	2-D-2/1	2002430	2042000	0	CL	0	CI	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2042001	2063000	0	CI	0	CI	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2063001	2089000	0	CL	0	CI	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2089001	2100500	0	CH	0	CI	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2100501	2105000	0	CH	0	CI	64	0	152B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2105001	2114500	0	CL	0	CI	64	0	152B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2114501	2138000	0	CL	0	CI	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2138001	2173000	0	CI	0	CI	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2173001	2212000	0	CL	0	CL	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	2
S	2-D-2/1	2212001	2481000	0	CL	0	CL	64	0	102B	21A	21AA	-0	-0	65	2 2-0	9	C	3
	049-A-2/0	501134	739000	0	0	0	0	51	0	42C	11A	1Z*	21A	21AA	65	25-0-0	8	C	6
	049-A-3/0	228500	411500	0	0	0	0	51	1	2Z*	51A	21AA	-0	-0	65	25-0-0	8	C	2
	049-A-3/0	411501	450914	0	0	0	0	51	1	2Z*	51A	21AA	-0	-0	65	25-0-0	7	C	6
	049-A-3/0	450915	879000	0	0	0	0	51	1	2Z*	32B	21A	21AA	-0	64	25-0-0	7	C	6
	049-A-3/0	879001	994750	0	0	0	0	51	2	2Z*	32B	21A	21AA	-0	64	25-0-0	7	C	6
	049-A-3/0	994751	1017499	0000		0000		0	0	000	000	000	000	000	0	25-0-0	X	0	0
	049-A-3/0	1017500	1097500	0	0	0	0	51	0	2Z*	32B	21A	21AA	-0	64	25-0-0	7	C	6
N	2-D-3/1	5801259	5822500	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	1515 2	6	C	2
N	2-D-3/1	5822501	5824000	0	PT	0	0	63	0	102C	21A	21AA	-0	-0	64	1515 2	6	C	2
N	2-D-3/1	5824001	5831500	0	PT	0	0	63	0	152C	21A	21AA	-0	-0	64	1515 2	6	C	2
N	2-D-3/1	5831501	5832000	0	CL	0	0	63	0	152C	21A	21AA	-0	-0	64	1515 2	6	C	2
N	2-D-3/1	5832001	5901832	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	1515 2	6	C	2
S	2-D-3/1	5801259	5822500	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	1515 2	6	C	2
S	2-D-3/1	5822501	5824000	0	PT	0	0	63	0	102C	21A	21AA	-0	-0	64	1515 2	6	C	2
S	2-D-3/1	5824001	5831500	0	PT	0	0	63	0	152C	21A	21AA	-0	-0	64	1515 2	6	C	2
S	2-D-3/1	5831501	5832000	0	CL	0	0	63	0	152C	21A	21AA	-0	-0	64	1515 2	6	C	2
S	2-D-3/1	5832001	5901832	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	1515 2	6	C	2
N	2-D-3/2	5901833	5947375	0	CL	0	0	63	1	102C	21A	21AA	-0	-0	64	1515 2	6	C	2
N	2-D-3/2	5947376	5996609	0	CL	0	0	63	1	102C	21A	21AA	-0	-0	64	2 2-0	6	C	2
N	2-D-3/2	5996610	6087963	0	CL	0	0	63	1	102C	21A	21AA	-0	-0	64	151515	6	C	2
N	2-D-3/2	6087964	6228000	0	CL	0	0	63	2	102C	21A	21AA	-0	-0	65	151515	6	C	2
N	2-D-3/2	6228001	6317336	0	CI	0	0	63	2	102C	21A	21AA	-0	-0	65	151515	6	C	2
N	2-D-3/2	6317337	6444000	0	CI	0	0	63	2	102C	21A	21AA	-0	-0	65	2 2-0	6	C	2
N	2-D-3/2	6444001	6480000	0	CI	0	0	63	2	152C	21A	21AA	-0	-0	65	2 2-0	6	C	2
N	2-D-3/2	6480001	6553310	0	CI	0	0	63	2	102C	21A	21AA	-0	-0	65	2 2-0	6	C	2
S	2-D-3/2	5901833	5947375	0	CL	0	0	63	1	102C	21A	21AA	-0	-0	64	1515 2	5	C	2
S	2-D-3/2	5947376	5996609	0	CL	0	0	63	1	102C	21A	21AA	-0	-0	64	2 2-0	5	C	2
S	2-D-3/2	5996610	6050000	0	CL	0	0	63	1	102C	21A	21AA	-0	-0	64	151515	5	C	2
S	2-D-3/2	6050001	6055000	0	CL	0	0	63	1	152C	21A	21AA	-0	-0	64	151515	5	C	2
S	2-D-3/2	6055001	6087963	0	CL	0	0	63	1	102C	21A	21AA	-0	-0	64	151515	5	C	2
S	2-D-3/2	6087964	6204639	0	CL	0	0	63	2	102C	21A	21AA	-0	-0	65	151515	5	C	2
S	2-D-3/2	6204640	6228000	0	CL	0	0	63	2	102C	21A	21AA	-0	-0	65	151515	6	C	2
S	2-D-3/2	6228001	6317336	0	CI	0	0	63	2	102C	21A	21AA	-0	-0	65	151515	6	C	2
S	2-D-3/2	6317337	6444000	0	CI	0	0	63	2	102C	21A	21AA	-0	-0	65	2 2-0	6	C	2
S	2-D-3/2	6444001	6480000	0	CI	0	0	63	2	152C	21A	21AA	-0	-0	65	2 2-0	6	C	2
S	2-D-3/2	6480001	6553310	0	CI	0	0	63	2	102C	21A	21AA	-0	-0	65	2 2-0	6	C	2

IDENTIFICATION INFORMATION: TRAV DIRN	HWY SEC SUB NO	START STATION	TO	END STATION	CHAIN EQN	SUB-GRADE INFO: N/T SOIL	CONTR BDY	EMB SOIL	YR FINISH	CONTR BDY	BASE COURSE INFORMATION: BOTTOM LAYER THICKNESS DESIGN CLASS BINDER	LAYER THICKNESS DESIGN CLASS BINDER	LAYER THICKNESS DESIGN CLASS BINDER	LAYER THICKNESS DESIGN CLASS BINDER	TOP LAYER THICKNESS DESIGN CLASS BINDER	YR FINISH	SURF COURSE INFO: THICKNESS (BOT … TOP)	AGG PIT	ASPH PEN	ASPH SUP
0	2-J-1/0	1821500		1976408	0	CH	0	0	61	0	72B	21A	21AA	-0	-0	65	2 2-0	4	C	6
0	2-J-1/0	1976409		2045288	0	CH	0	0	61	0	72C	21A	21AA	-0	-0	65	2 2-0	4	C	6
N	2-D-3/1	5400910		5446200	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	2 2-0	3	C	1
N	2-D-3/1	5446201		5628500	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	0 0 0	X	0	0
N	2-D-3/1	5628501		5734000	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	2-0-0	3	C	1
N	2-D-3/1	5734001		5801258	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	2-0-0	2	C	1
S	2-D-3/1	5400910		5505579	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	2 2-0	3	C	1
S	2-D-3/1	5505580		5611179	0	CL	0	0	63	0	102C	41AA	-0	-0	-0	64	2 2-0	3	C	1
S	2-D-3/1	5611180		5666774	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	2 2-0	3	C	1
S	2-D-3/1	5666775		5801258	0	CL	0	0	63	0	102C	21A	21AA	-0	-0	64	2-0-0	2	C	1
WA	1-C-1/2	431385		438300	0	CI	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	1	C	3
WA	1-C-1/2	438301		446200	0	CI	0	0	56	0	189	71A	21AA	21AP	21AP	57	1515-0	1	C	3
WA	1-C-1/2	446201		465700	0	CI	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	1	C	3
WA	1-C-1/2	465701		471000	0	CI	0	0	56	0	129	71A	21AA	21AP	21AP	57	1515-0	1	C	3
WA	1-C-1/2	471001		476000	0	CI	0	0	56	0	129	71A	21AA	21AP	21AP	57	2 2-0	1	C	3
WA	1-C-1/2	476001		488400	0	CL	0	0	56	0	129	71A	21AA	21AP	21AP	57	2 2-0	1	C	3
WA	1-C-1/2	488401		491000	0	CL	0	0	56	0	71A	21AA	21AP	21AP	-0	57	2 2-0	1	C	3
WA	1-C-1/2	491001		514000	0	CL	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	1	C	3
WA	1-C-1/2	514001		704782	0	CI	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	1	C	3
WA	1-C-1/2	704783		787000	0	CI	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	0	C	3
WA	1-C-1/2	787001		812000	0	CL	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	0	C	3
WA	1-C-1/2	812001		854002	0	CI	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	0	C	3
WA	1-C-1/2	854003		874000	0	CI	0	0	56	0	71A	21AA	21AP	21AP	-0	57	2 2-0	0	C	3
WA	1-C-1/2	874001		932000	0	CI	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	0	C	3
WA	1-C-1/2	932001		943500	0	CH	0	0	56	0	71A	21AA	21AP	21AP	-0	57	1515-0	0	C	3
EA	1-C-1/2	431385		476000	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	1	C	3
EA	1-C-1/2	476001		514000	0	CL	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	1	C	3
EA	1-C-1/2	514001		704782	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	1	C	3
EA	1-C-1/2	704183		712000	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	0	C	3
EA	1-C-1/2	712001		735000	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2525-0	0	C	3
EA	1-C-1/2	735001		787000	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	0	C	3
EA	1-C-1/2	787001		812000	0	CL	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	0	C	3
EA	1-C-1/2	812001		932000	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	0	C	3
EA	1-C-1/2	932001		943500	0	CH	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	0	C	3
WA	1-C-1/3	943501		959000	0	CH	0	0	57	0	71A	21AA	21AP	21AP	-0	57	1515-0	0	C	3
WA	1-C-1/3	959001		988000	0	CI	0	0	57	0	71A	21AA	21AP	21AP	-0	57	1515-0	0	C	3
EA	1-C-1/3	943501		946000	0	CH	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	0	C	3
EA	1-C-1/3	946001		959000	0	CH	0	0	64	0	102B	21A	21AA	-0	-0	65	2525-0	0	C	3
EA	1-C-1/3	959001		972000	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2525-0	0	C	3
EA	1-C-1/3	972001		988000	0	CI	0	0	64	0	102B	21A	21AA	-0	-0	65	2 2-0	0	C	3

the "year finished" column. By coincidence the division at station 2173+00.0 had already been made, so no new inventory sections were formed.

Stage 4 input consisted of one data card and will not be discussed as no new concept is involved.

Stage 5 input consisted of three data cards, the first of which contained 0 N 2-D-2/1 2002430-2100500 and the "base course information" which is shown in lines one to four of the stage 5 output. A division was made at station 2100+50.0 which created two inventory sections in place of the previous inventory section. The creation of these new sections was necessary because of a change in the thickness of the bottom layer of base course. A similar division was made at station 2114+50.0.

Stage 6 input (one card) produced no new inventory sections.

Stage 7 input consisted of two data cards, and a division was made at station 2403+88.7 due to the change in asphalt cement supply. The basic inventory sections to be used for studying cracking and/or other problems have now been established. Each section has basic properties which differ in some way from the adjoining sections.

The output shown in the subsequent pages represents only stage 7 "print-out," since all the input information is represented in this stage. All the pavement sections which are associated with the series tested in the testing program of this investigation are contained in

FIGURE D1. An explanation of the less obvious coding used in the output is given on page D6.

Analysis of Test Results

The computer program and the output for one of the thirteen test series is given in FIGURE D2. The function of this program has been explained in CHAPTER III.

```
18C049     CURVE PROPERTIES PRO                    FORTRAN SOURCE LIST
       ISN        SOURCE STATEMENT

         0 $IBFTC CURVES   NODECK
             C
             C
             C          THIS PROGRAM COMPUTES THE CCORDINATES OF THE AVERAGE
             C          CURVE FOR EACH TEST SERIES, THE UPPER AND LOWER
             C          2 STANDARD DEVIATION STRESS BANDS, AND THE 2 STANDARD
             C          DEVATION FAILURE STRAIN POINTS.
             C
             C
         1         NCOUNT=0
         2     232 NCOUNT=NCOUNT+1
         3         DIMENSION  IL(18,34),IT(18),IDI(18),IN(18),L(18,34),T(18),DI(18),
                  1TS(18,34),E(18,34),SUMTS(34),SUME(34),EAVG(34),TSAVG(34),S(18),
                  2SUMS(18),SI(18),SUMSI(18),D(18),SUMD(18),SDTS(34),UPBAND(34),
                  3DOBAND(34),SUMF(18),F(18),EE(18)
         4         INTEGER A,B,C
         5         REAL L
         6         IF(NCOUNT.LE.11) C=18
        11         IF(NCOUNT.GE.12) C=13
        14         DO208A=1,C
        15         READ(5,2001) (IL(A,B),B=1,34),IN(A),IT(A),IDI(A),IPIT,IPEN,ISUP
        25     208 CONTINUE
        27    2001 FORMAT (34I2,1X,1I2,2I3,1I1,1A1,1I1)
        30         DO201A=1,C
        31         T(A)=IT(A)
        32         DI(A)=IDI(A)
        33     201 CONTINUE
        35         DO200A=1,C
        36         DO200B=1,34
        37         L(A,B)=IL(A,B)
        40         TS(A,B)=(200.*L(A,B))/(.000314*T(A)*DI(A))
        41     200 CONTINUE
        44         DO241A=1,C
        45         B=0
        46     221 B=B+1
        47         IF(TS(A,B+1).GE.TS(A,B))GO TO 221
        52         EE(A)=B
        53     241 CONTINUE
        55         DO202B=1,34
        56         SUMTS(B)=0
        57         SUME(B)=0
        60         DO202A=1,C
        61         E(A,B)=B
        62     204 IF(TS(A,B).GT.0.) GO TO 203
        65         TS(A,B)=TS(A,B-1)
        66         E(A,B)=E(A,B-1)
        67         GO TO 204
        70     203 CONTINUE
        71         SUME(B)=SUME(B) + E(A,B)
        72         SUMTS(B)=SUMTS(B) + TS(A,B)
        73     202 CONTINUE
        76         CC=C
        77         WRITE(6,2200)
       100    2200 FORMAT(29H COORDINATES OF AVERAGE CURVE)
       101         DO206B=1,34
```

FIG. D2: TEST RESULTS PROGRAM AND SAMPLE OUTPUT [PAGE DI2 TO DI4 INCLUSIVE]

```
180049    CURVE PROPERTIES PRO                    FORTRAN SOURCE LIST CURVES
        ISN         SOURCE STATEMENT

        102         EAVG(B)=(SUME(B))/((CC)*(10000.))
        103         TSAVG(B)=(SUMTS(B))/(CC)
        104         WRITE(6,2002) EAVG(B),TSAVG(B),IPIT,IPEN,ISUP
        105    2002 FORMAT (1X,F10.6,3X,F8.0,10X,I11,1A1,I11)
        106     206 CONTINUE
        110         WRITE(6,2300)
        111    2300 FORMAT(23H STRESS DEVIATION BANDS)
        112         DO212B=1,34
        113         DO211A=1,C
        114         SUMD(0)=0
        115     214 IF(TS(A,B).GT.0.) GO TO 213
        120         TS(A,B)=TS(A,B-1)
        121         GO TO 214
        122     213 CONTINUE
        123         D(A)=(TSAVG(B)-TS(A,B))**2
        124         SUMD(A)=SUMD(A-1)+D(A)
        125     211 CONTINUE
        127         SDTS(B)=SQRT((SUMD(C))/(CC-1.))
        130         UPBAND(B)=(TSAVG(B))+(2.*(SDTS(B)))
        131         DOBAND(B)=(TSAVG(B))-(2.*(SDTS(B)))
        132         WRITE(6,2003) UPBAND(B),DOBAND(B)
        133    2003 FORMAT(3X,F8.0,6X,F8.0)
        134     212 CONTINUE
        136         WRITE(6,2400)
        137    2400 FORMAT(32H FAILURE STRAIN DEVIATION POINTS)
        140         DO222A=1,C
        141         SUMF(0)=0
        142         F(A)=((EAVG(34)*10000.)-EE(A))**2
        143         SUMF(A)=SUMF(A-1)+F(A)
        144     222 CONTINUE
        146         SDE=SQRT((SUMF(C))/(CC-1.))
        147         EBANDU=(EAVG(34))+(2.*(SDE)*0.0001)
        150         EBANDL=(EAVG(34))-(2.*(SDE)*0.0001)
        151         WRITE(6,2004) EBANDL,EBANDU
        152    2004 FORMAT(6X,F10.6,6X,F10.6)
        153         IF(NCOUNT.LT.14) GO TO 232
        156         STOP
        157         END
```

```
OBJECT PROGRAM IS BEING ENTERED INTO STORAGE.
COORDINATES OF AVERAGE CURVE
 0.000100      102.       9C1
 0.000200      212.       9C1
 0.000300      313.       9C1
 0.000394      394.       9C1
 0.000483      447.       9C1
 0.000550      475.       9C1
 0.000611      488.       9C1
 0.000656      492.       9C1
 0.000683      493.       9C1
 0.000694      494.       9C1
 0.000706      494.       9C1
 0.000717      494.       9C1
 0.000722      494.       9C1
 0.000728      494.       9C1
 0.000733      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
 0.000739      494.       9C1
STRESS DEVIATION BANDS
     241.        -36.
     371.         52.
     454.        172.
     508.        279.
     532.        362.
     538.        412.
     548.        427.
     553.        431.
     554.        432.
     555.        433.
     555.        433.
     557.        432.
     557.        432.
     557.        432.
     557.        432.
     557.        432.
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     557.        432.
     557.        432.
     557.        432.
     557.        432.
     557.        432.
     557.        432.
     557.        432.
     557.        432.
    1019.      -1019.
FAILURE STRAIN DEVIATION POINTS
      0.000125       0.001353
```